On the hyperfine anomaly and precision searches for new physics

Jacinda Ginges

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Australian Government
Australian Research Council

INT-24-1 Fundamental Physics with Radioactive Molecules

Overview

Testing the SM and searching for new physics in atoms

- Atomic parity violation
- Time-reversal-violating electric dipole moments

Adventures at the intersection of atomic and nuclear physics

- Case study in the hyperfine structure

Overview

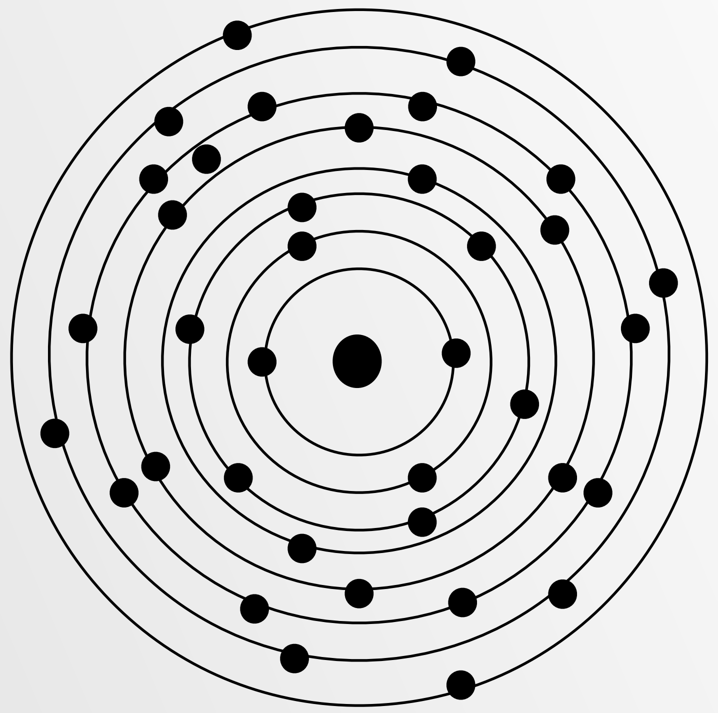
Testing the SM and searching for new physics in atoms

- Atomic parity violation
- Time-reversal-violating electric dipole moments

Adventures at the intersection of atomic and nuclear physics

- Case study in the hyperfine structure

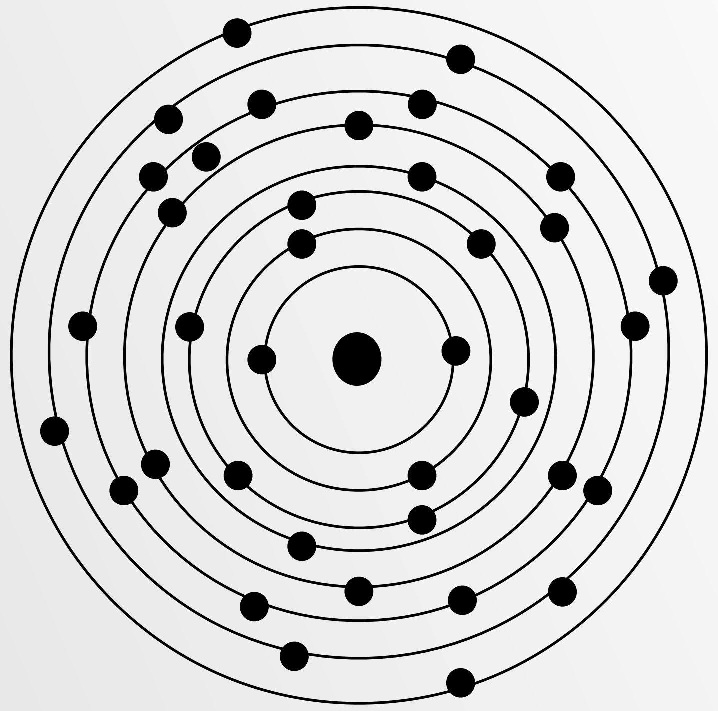
The atom as a laboratory for new physics searches



- Electromagnetic interaction
- Weak interaction
- Strong interaction

are present in atoms and may be probed and tested

The atom as a laboratory for new physics searches



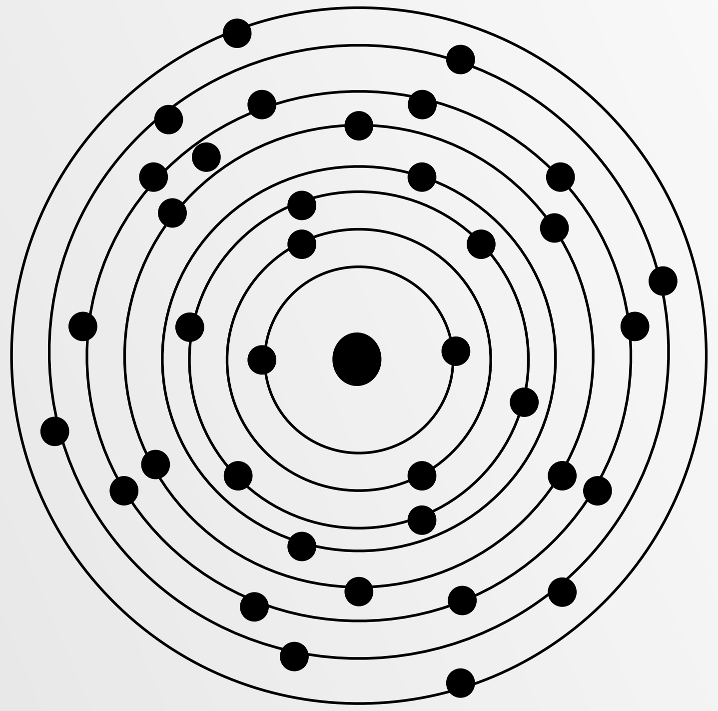
- Electromagnetic interaction
- Weak interaction
- Strong interaction

are present in atoms and may be probed and tested

Weak interaction does not conserve parity, $\boldsymbol{r} \rightarrow -\boldsymbol{r}$

May be *isolated* by studying parity-violating effects

The atom as a laboratory for new physics searches



- Electromagnetic interaction
- Weak interaction
- Strong interaction

are present in atoms and may be probed and tested

Weak interaction does not conserve parity, $\boldsymbol{r} \rightarrow -\boldsymbol{r}$

May be *isolated* by studying parity-violating effects

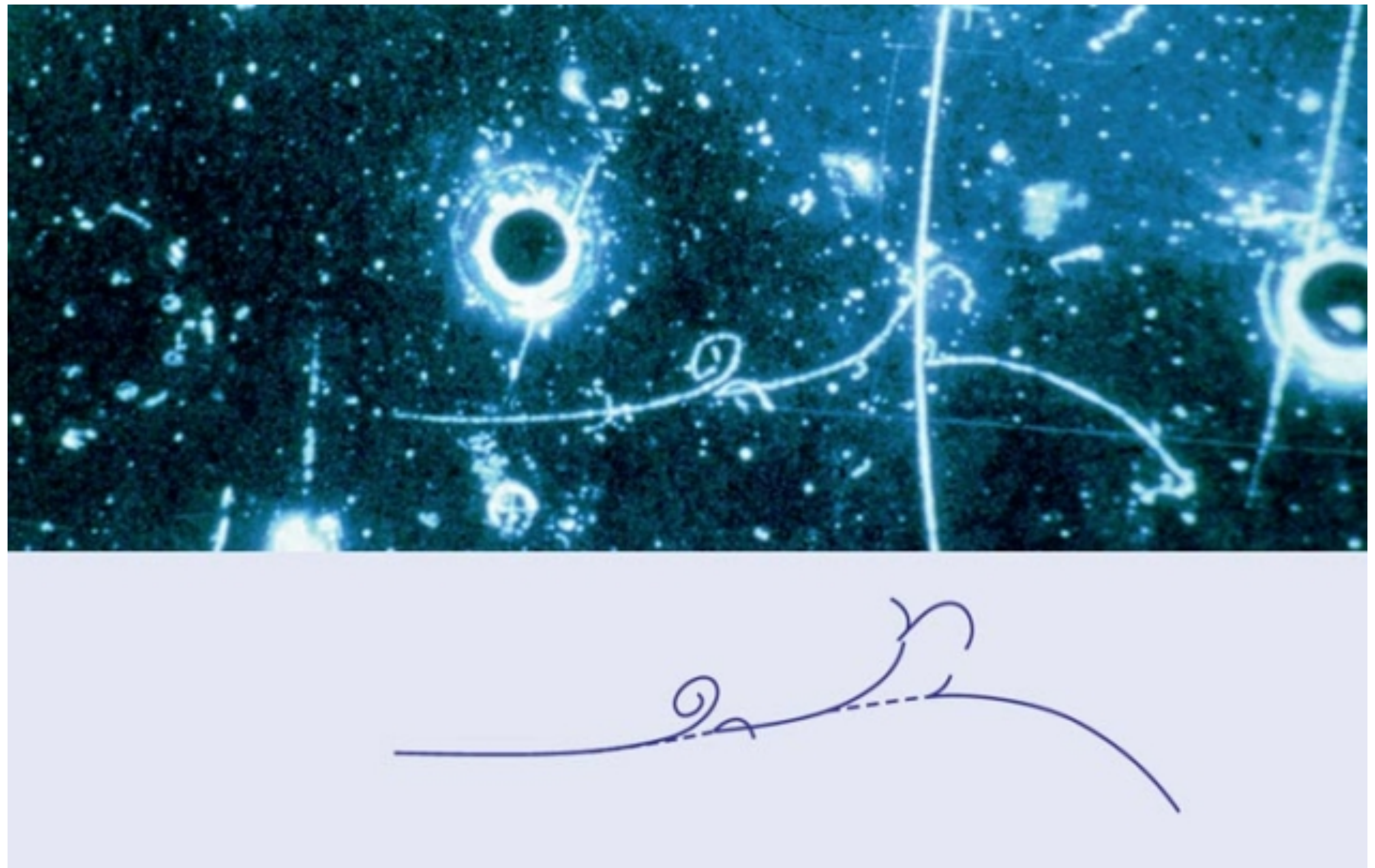
Complexity/simplicity of system may be varied by changing nuclear charge (Z), isotope, ionisation degree, state

- Possibilities for enhancement
- May choose more theoretically tractable system

Neutral weak currents

- Discovered at CERN (1973) in neutrino-nucleon and antineutrino-electron scattering experiments

Hadronic neutral current event: neutrino-nucleon scattering



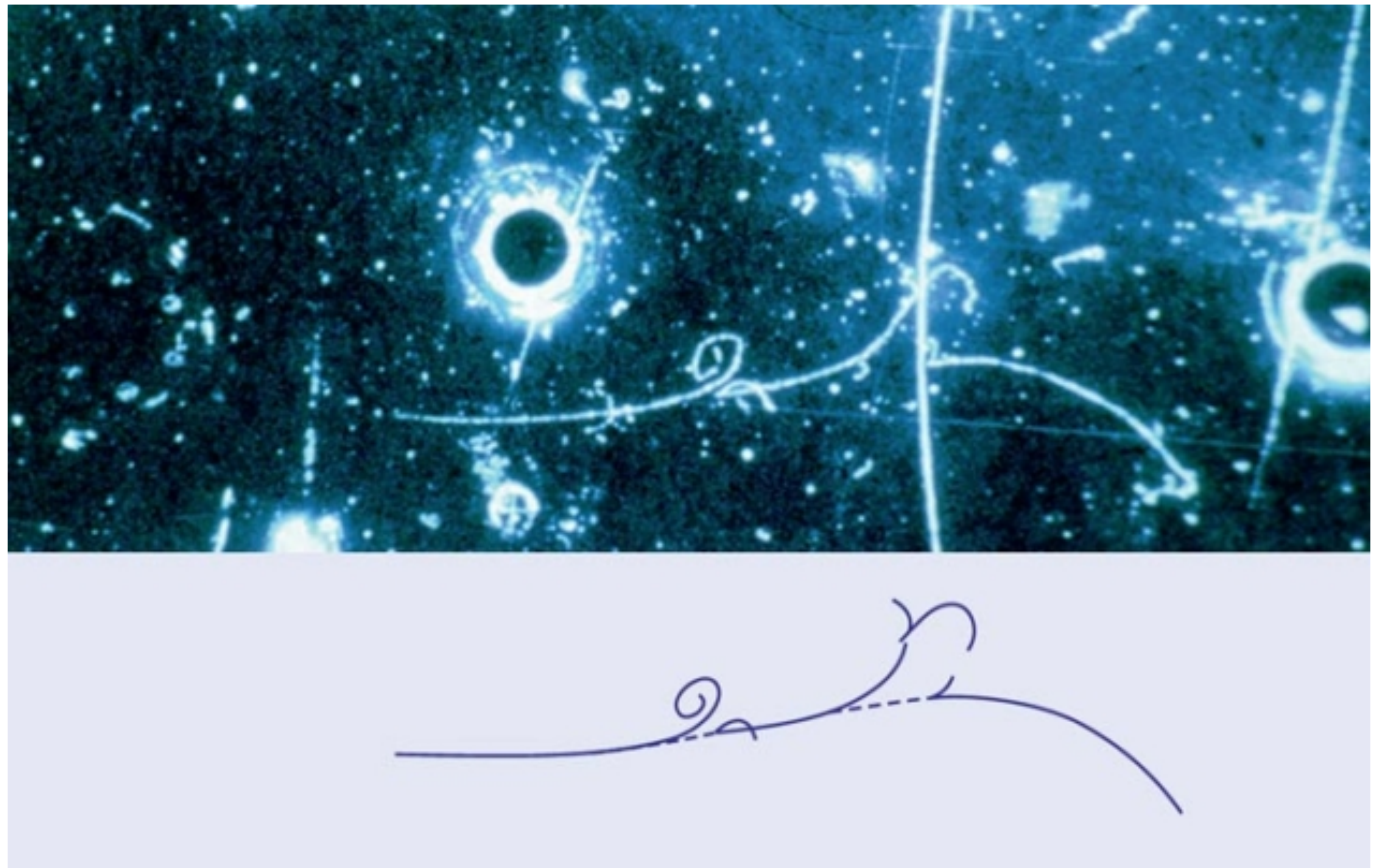
Leptonic neutral current event: antineutrino-electron scattering

https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/

Neutral weak currents

- Discovered at CERN (1973) in neutrino-nucleon and antineutrino-electron scattering experiments
- *Electron-nucleon interactions* first seen in atomic parity violation experiment with Bi at Novosibirsk, Russia (1978)

Hadronic neutral current event: neutrino-nucleon scattering



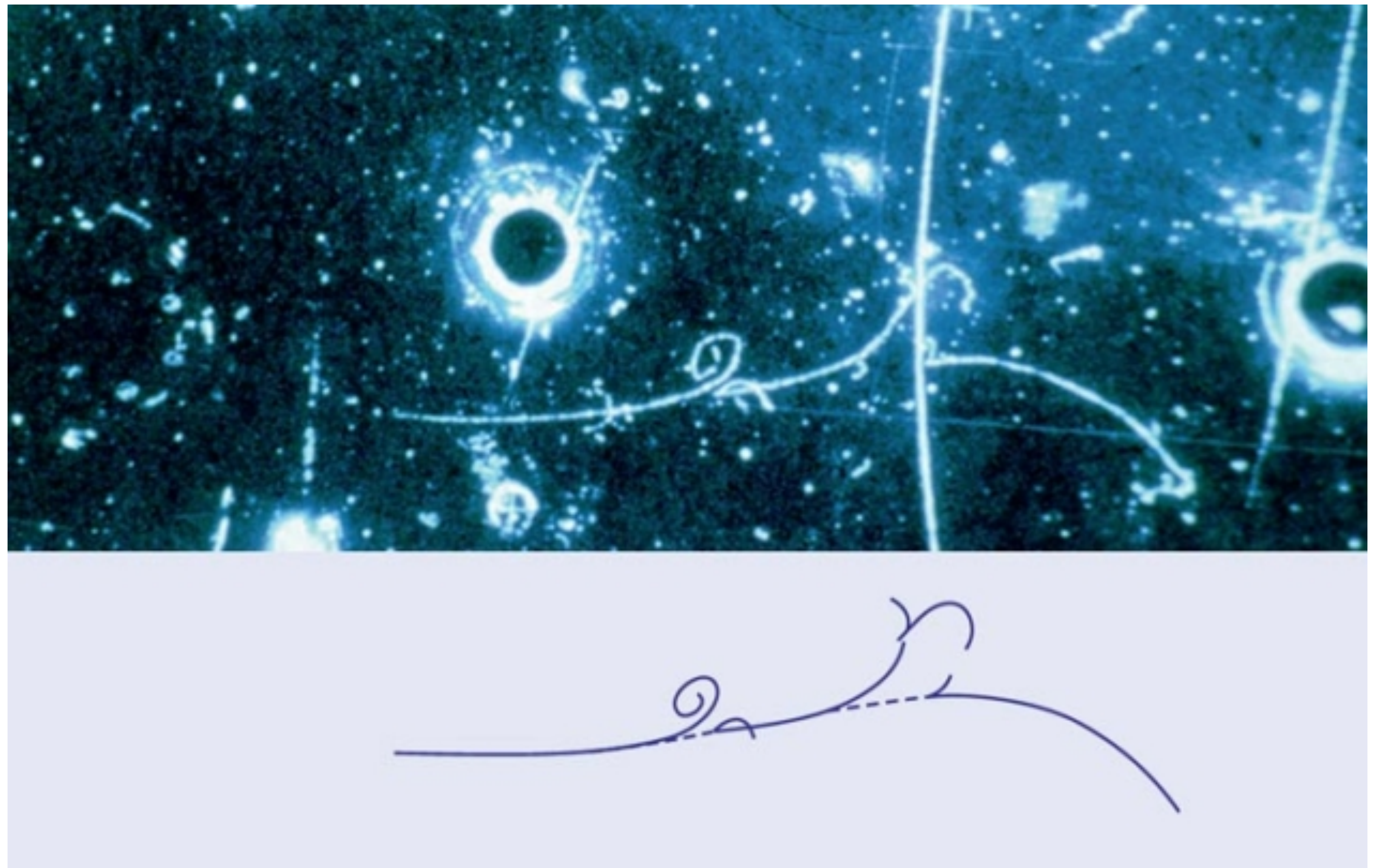
Leptonic neutral current event: antineutrino-electron scattering

https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/

Neutral weak currents

- Discovered at CERN (1973) in neutrino-nucleon and antineutrino-electron scattering experiments
- *Electron-nucleon interactions* first seen in atomic parity violation experiment with Bi at Novosibirsk, Russia (1978)
- e-N interactions seen shortly after in scattering of electrons off deuterons and protons at SLAC (1978)

Hadronic neutral current event: neutrino-nucleon scattering

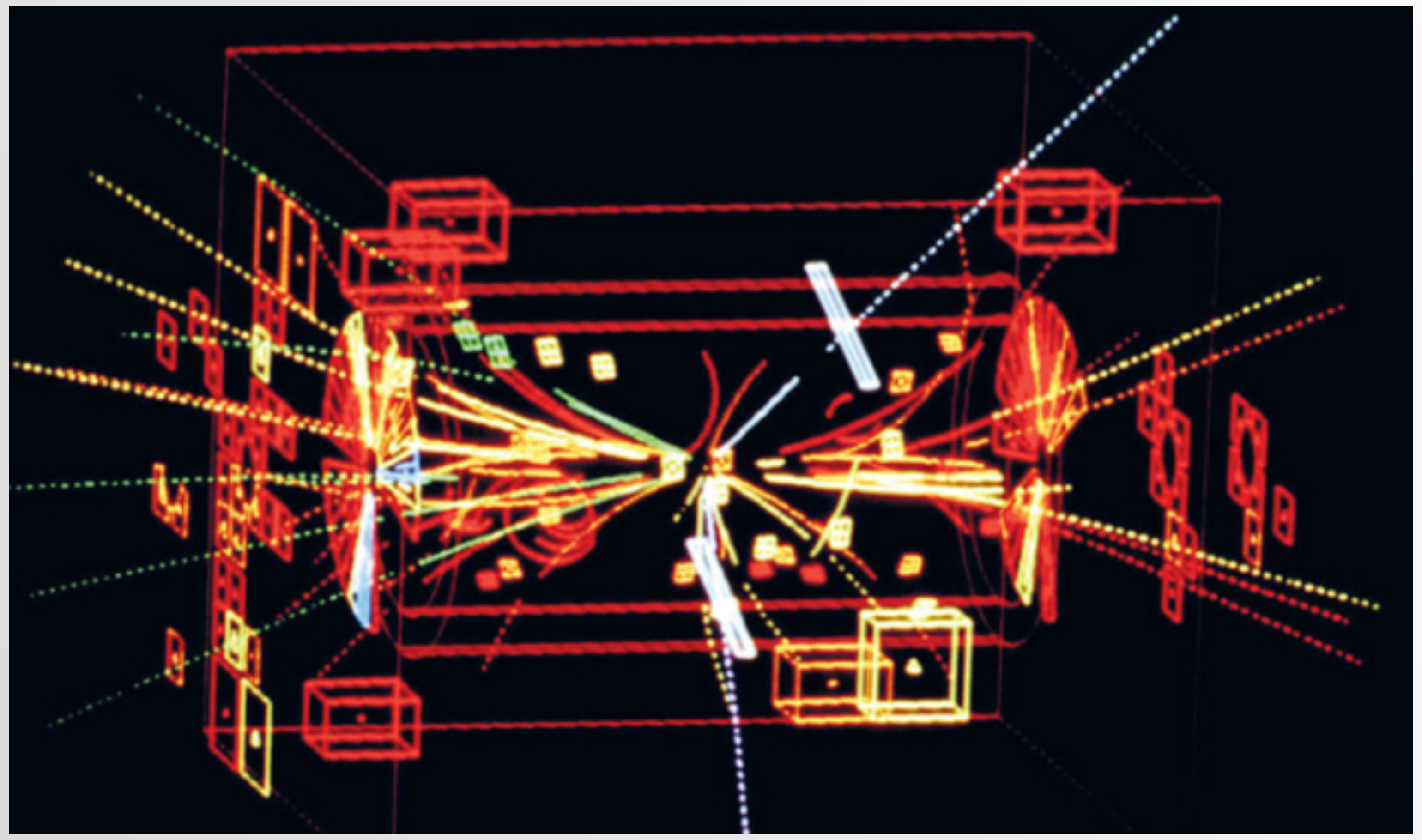


Leptonic neutral current event: antineutrino-electron scattering

https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/

Neutral weak currents

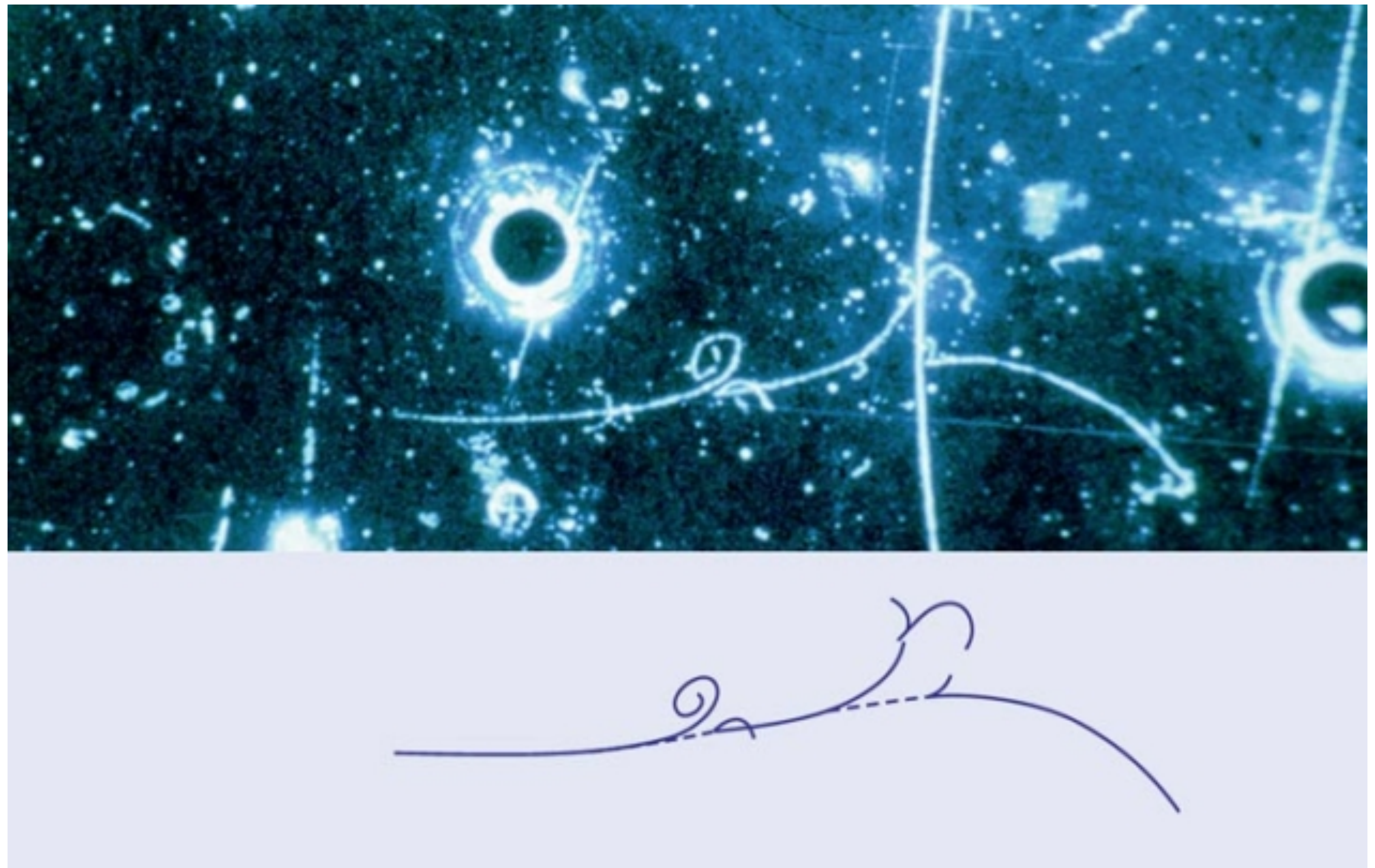
- Discovered at CERN (1973) in neutrino-nucleon and antineutrino-electron scattering experiments
- *Electron-nucleon interactions* first seen in atomic parity violation experiment with Bi at Novosibirsk, Russia (1978)
- e-N interactions seen shortly after in scattering of electrons off deuterons and protons at SLAC (1978)



- Z, W^+, W^- produced directly at CERN (1983)

https://cerncourier.com/a/finding-the-w-and-z/

Hadronic neutral current event: neutrino-nucleon scattering

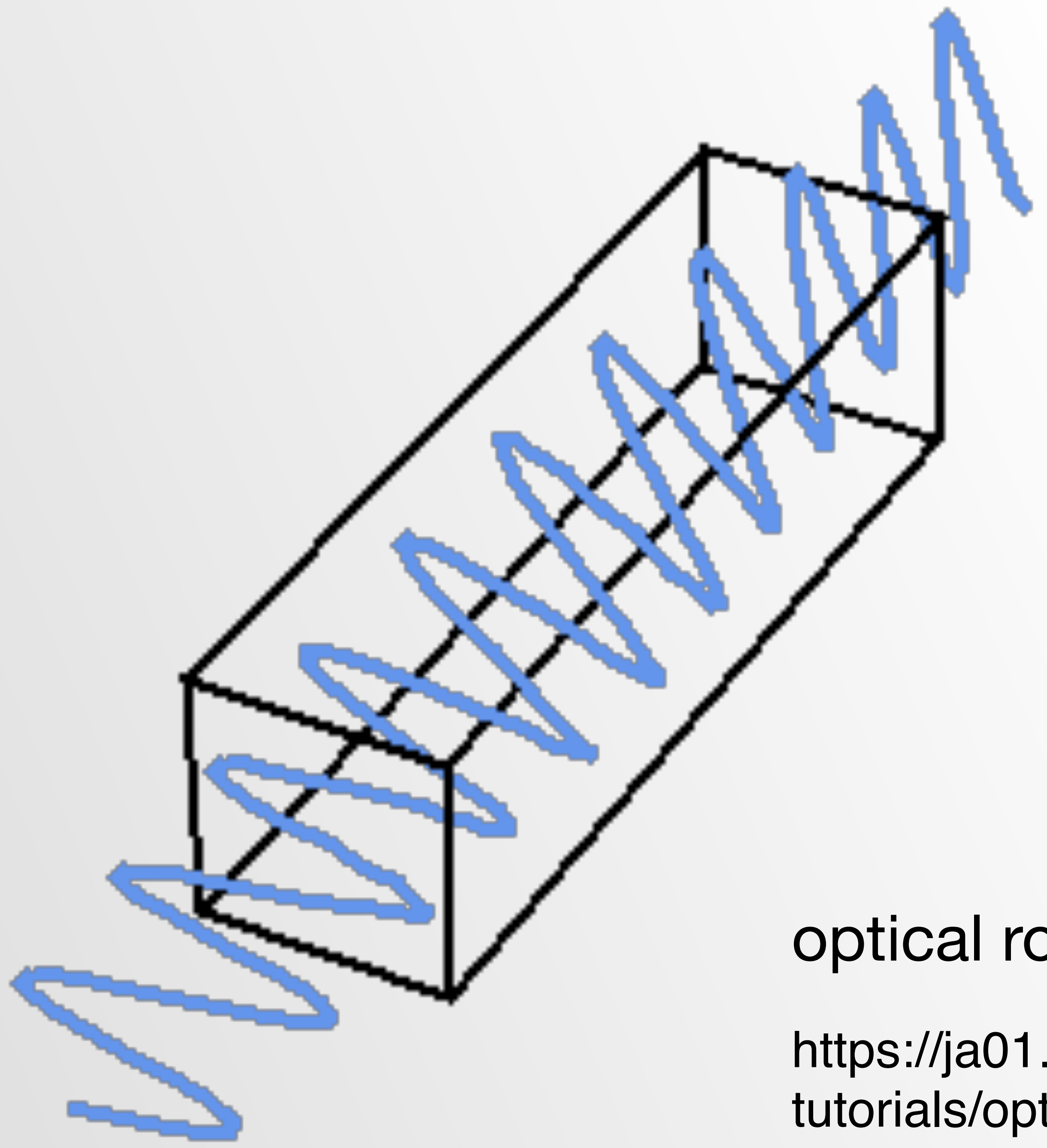


Leptonic neutral current event: antineutrino-electron scattering

https://cerncourier.com/a/neutral-currents-a-perfect-experimental-discovery/

Bismuth experiment

- e-N weak interaction produces optical activity
- Plane of polarisation of light is *rotated* on passing through bismuth vapour
- *Coherent, macroscopic parity-violating effect*

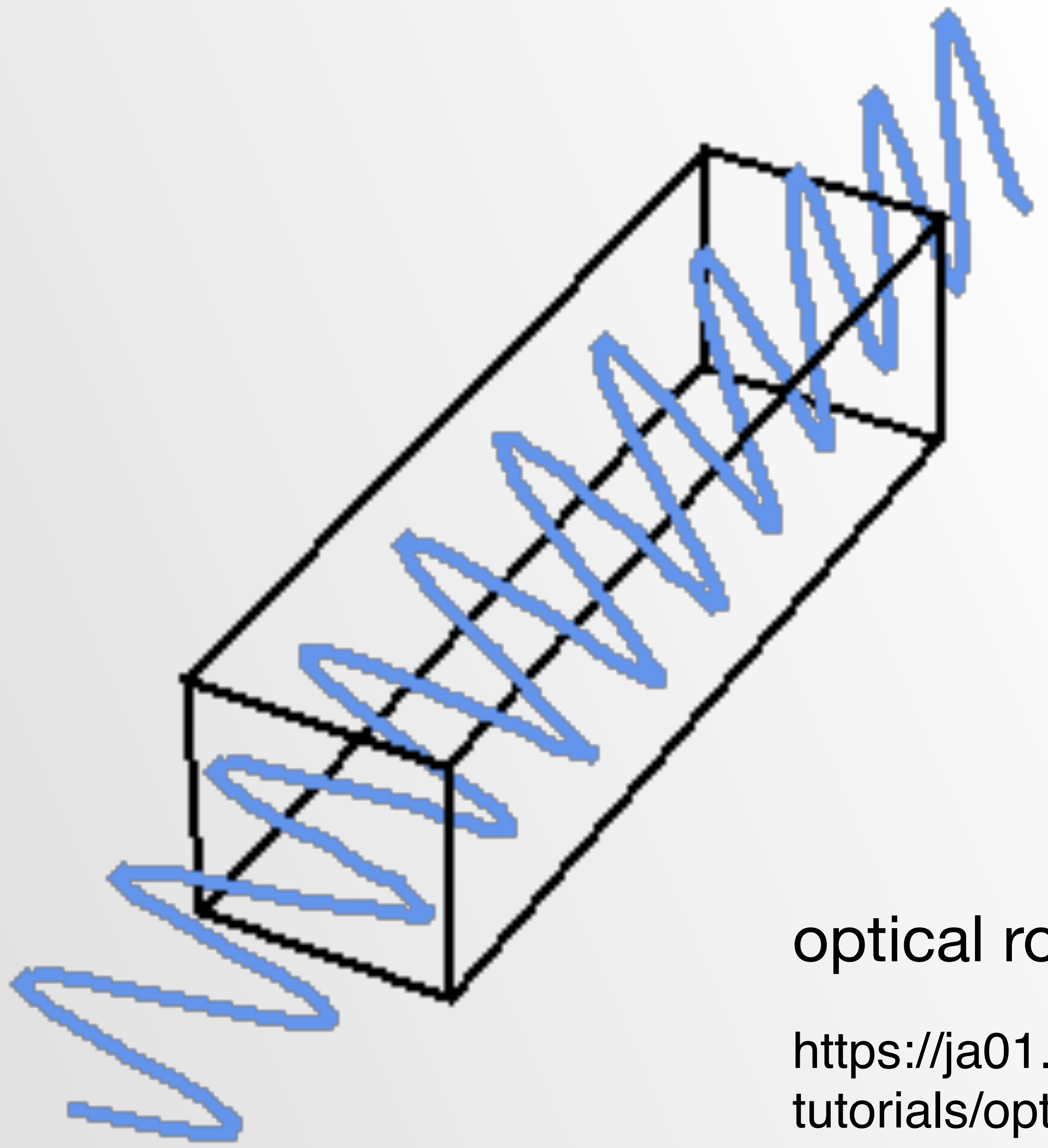


optical rotation animation

https://ja01.chem.buffalo.edu/tutorials/opticalactivity.html

Bismuth experiment

- e-N weak interaction produces optical activity
- Plane of polarisation of light is *rotated* on passing through bismuth vapour
- *Coherent, macroscopic parity-violating effect*



optical rotation animation

https://ja01.chem.buffalo.edu/tutorials/opticalactivity.html

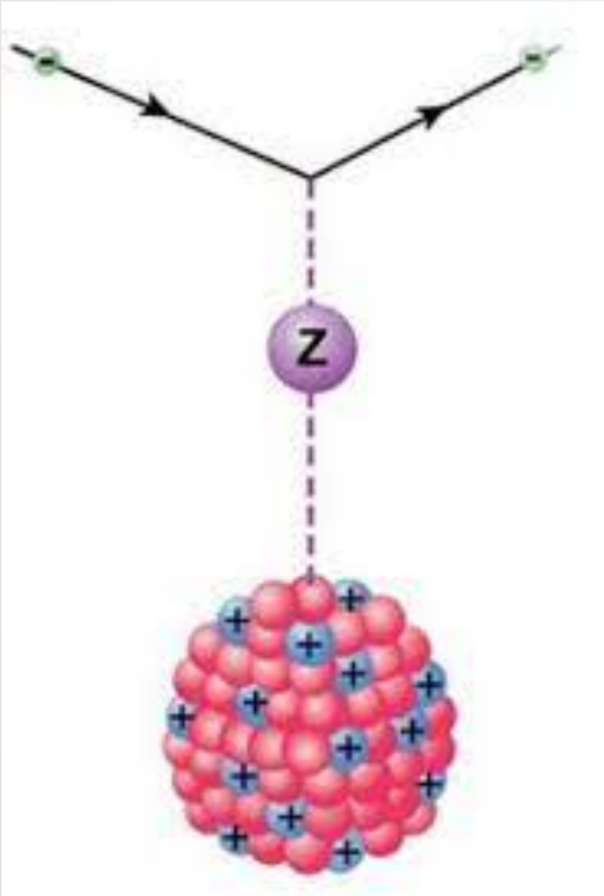
The discovery of a new kind of a parity nonconserving weak interaction of electrons with nucleons is an example of a situation when a branch of physics (in this case, atomic spectroscopy) long since believed to be classical, again proves to be at the forefront of our understanding of nature… Table-top apparatus has proved to be an important addition to the experimental methods traditional for elementary particle physics. I am convinced that this case is not the last and that the time of table-top experiments in studying fundamental properties of matter is far from over.

— *I. B. Khriplovich*

Violations of fundamental symmetries in atoms

Precision atomic theory *needed* to extract fundamental parameters from atomic experiments for comparison with SM

Atomic parity violation (APV)



APV amplitude:

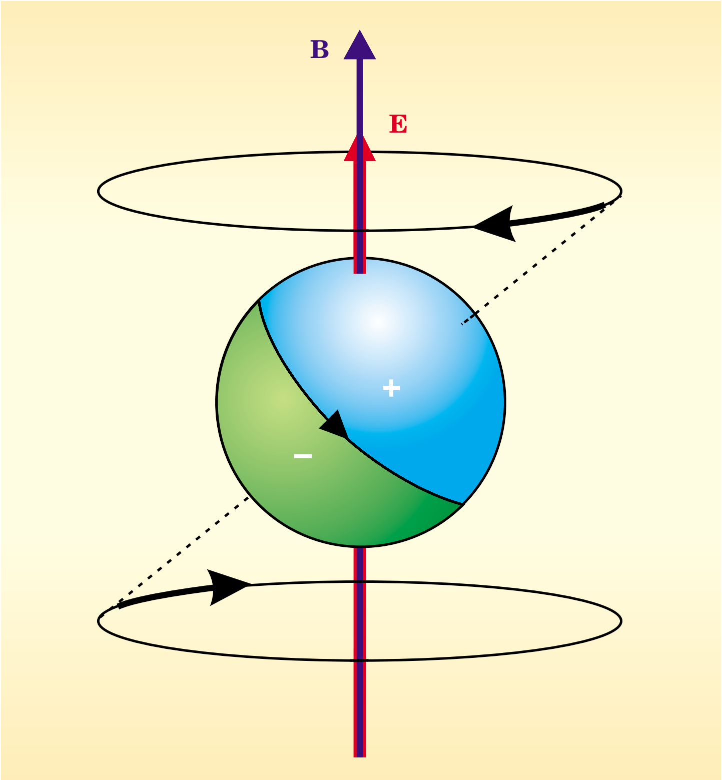
$$E_{PV} = \xi \, Q_W$$

from atomic structure theory (ξ)

nuclear weak charge (Q_W)

Electric dipole moments (EDMs)

Parity- and time-reversal-violating



Atomic EDM:

$$d_{atom} = \zeta S + K d_e + \ldots$$

from atomic structure theory (ζ, K)

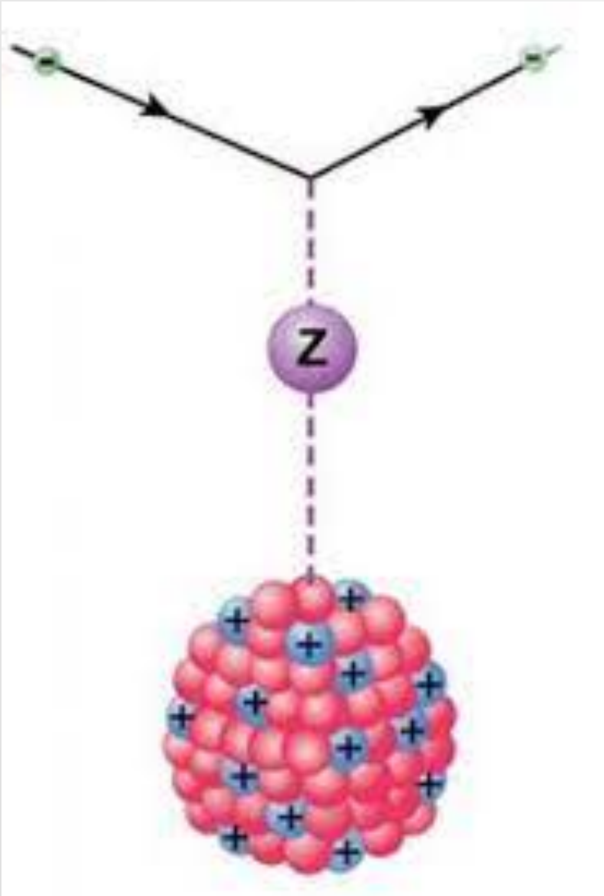
nuclear Schiff moment (S)

electron EDM (d_e)

Violations of fundamental symmetries in atoms

Precision atomic theory *needed* to extract fundamental parameters from atomic experiments for comparison with SM

Atomic parity violation (APV)



APV amplitude:

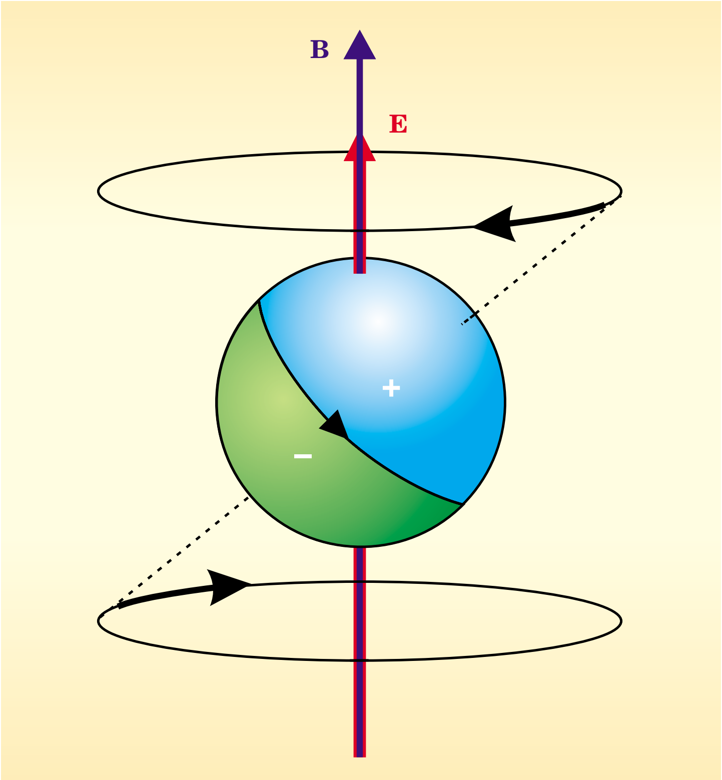
$$E_{PV} = \xi Q_W$$

from atomic structure theory

nuclear weak charge

Electric dipole moments (EDMs)

Parity- and time-reversal-violating



Atomic EDM:

$$d_{atom} = \zeta S + K d_e + \ldots$$

from atomic structure theory

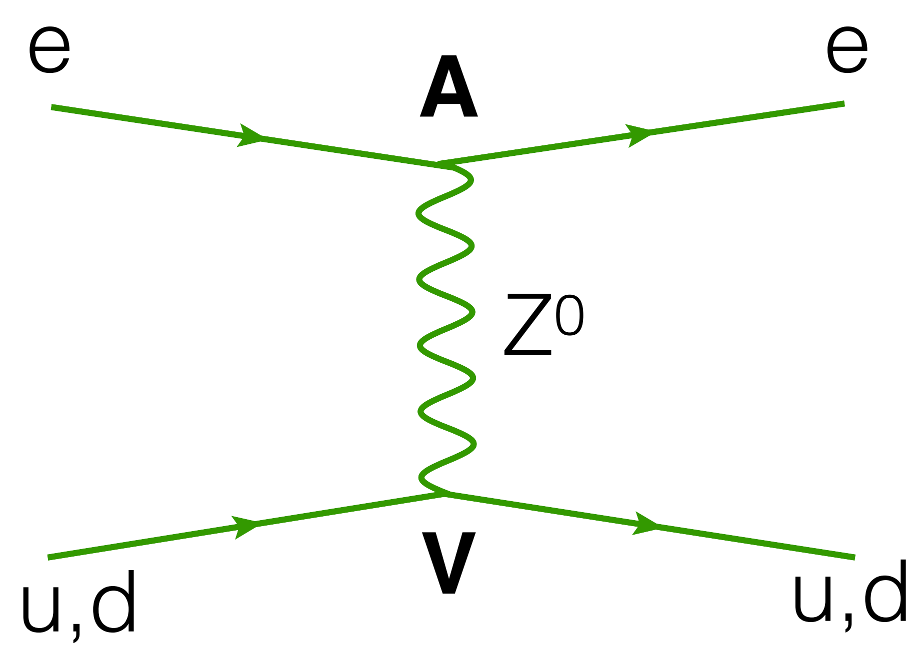
nuclear Schiff moment

electron EDM

Atomic parity violation and the nuclear weak charge

Axial vector coupling to electrons,
vector coupling to quarks

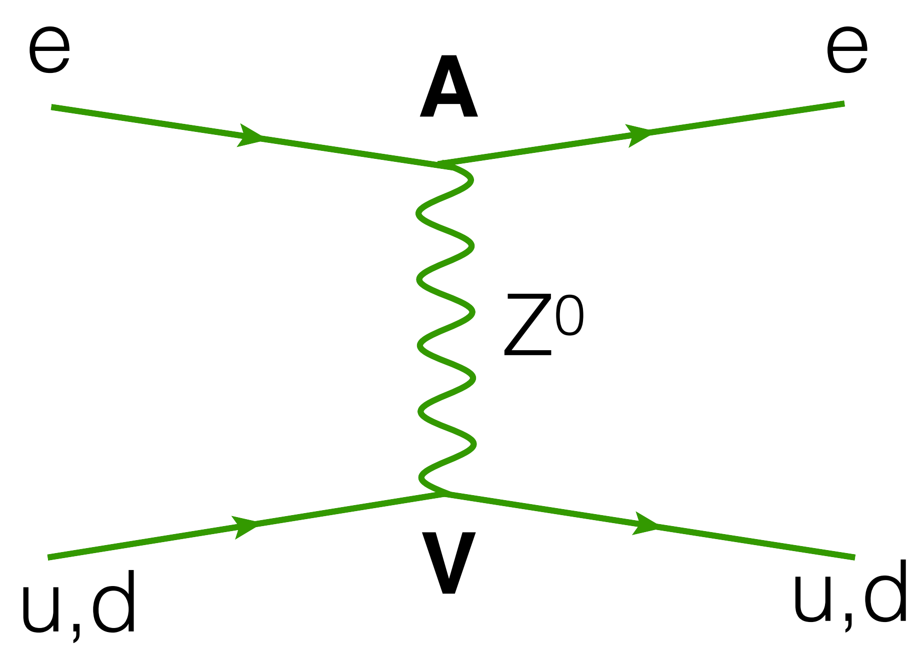
$$\frac{G}{\sqrt{2}} C_{1q} \left(\bar{e}\gamma_\mu \gamma_5 e\right)\left(\bar{q}\gamma^\mu q\right)$$



Atomic parity violation and the nuclear weak charge

Axial vector coupling to electrons,
vector coupling to quarks

$$\frac{G}{\sqrt{2}} C_{1q} \left(\bar{e}\gamma_\mu\gamma_5 e\right)\left(\bar{q}\gamma^\mu q\right)$$



Standard model tree-level couplings

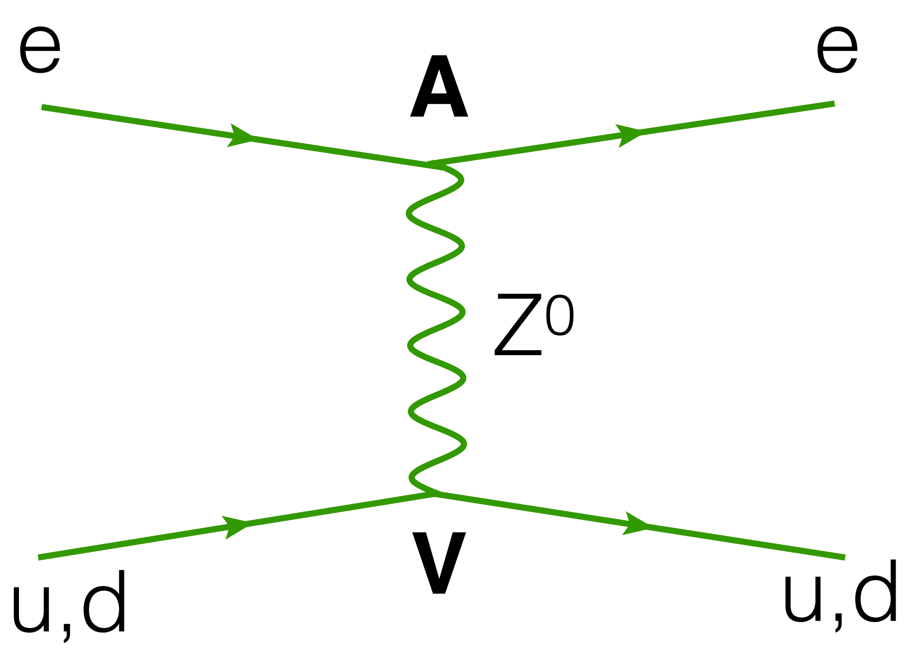
$$C_{1n} = C_{1u} + 2C_{1d} = -\frac{1}{2}$$

$$C_{1p} = 2C_{1u} + C_{1d} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right)$$

Atomic parity violation and the nuclear weak charge

Axial vector coupling to electrons,
vector coupling to quarks

$$\frac{G}{\sqrt{2}} C_{1q} \left(\bar{e}\gamma_\mu\gamma_5 e\right)\left(\bar{q}\gamma^\mu q\right)$$



Standard model tree-level couplings

$$C_{1n} = C_{1u} + 2C_{1d} = -\frac{1}{2}$$
$$C_{1p} = 2C_{1u} + C_{1d} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right)$$

Leads to parity-violating interaction Hamiltonian for electrons

$$h_{\mathrm{PV}} = -\frac{G}{2\sqrt{2}} Q_W \rho(r)\gamma_5$$

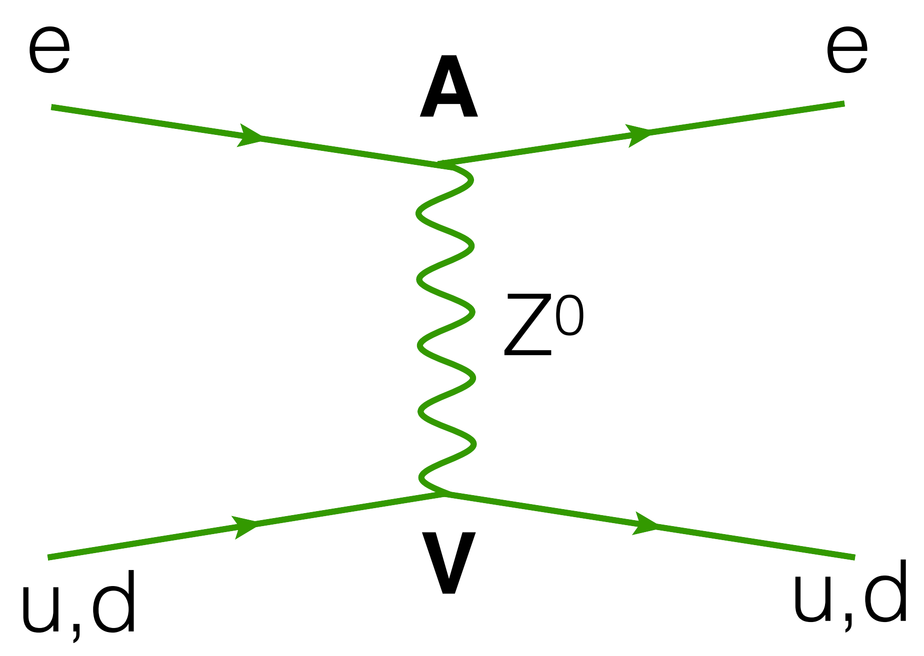
where Q_W is *nuclear weak charge.*

SM value known well, $Q_W^{\mathrm{SM}} = -73.23(1)$

Atomic parity violation and the nuclear weak charge

Axial vector coupling to electrons,
vector coupling to quarks

$$\frac{G}{\sqrt{2}} C_{1q} \left(\bar{e}\gamma_\mu \gamma_5 e\right)\left(\bar{q}\gamma^\mu q\right)$$



Standard model tree-level couplings

$$C_{1n} = C_{1u} + 2C_{1d} = -\frac{1}{2}$$
$$C_{1p} = 2C_{1u} + C_{1d} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right)$$

Leads to parity-violating interaction Hamiltonian for electrons

$$h_{\rm PV} = -\frac{G}{2\sqrt{2}} Q_W \rho(r)\gamma_5$$

where Q_W is *nuclear weak charge.*

SM value known well, $Q_W^{\rm SM} = -73.23(1)$

Parity-violating nature

Non-relativistic limit:

$$h_{\rm PV} \propto \boldsymbol{\sigma} \cdot \mathbf{p}$$

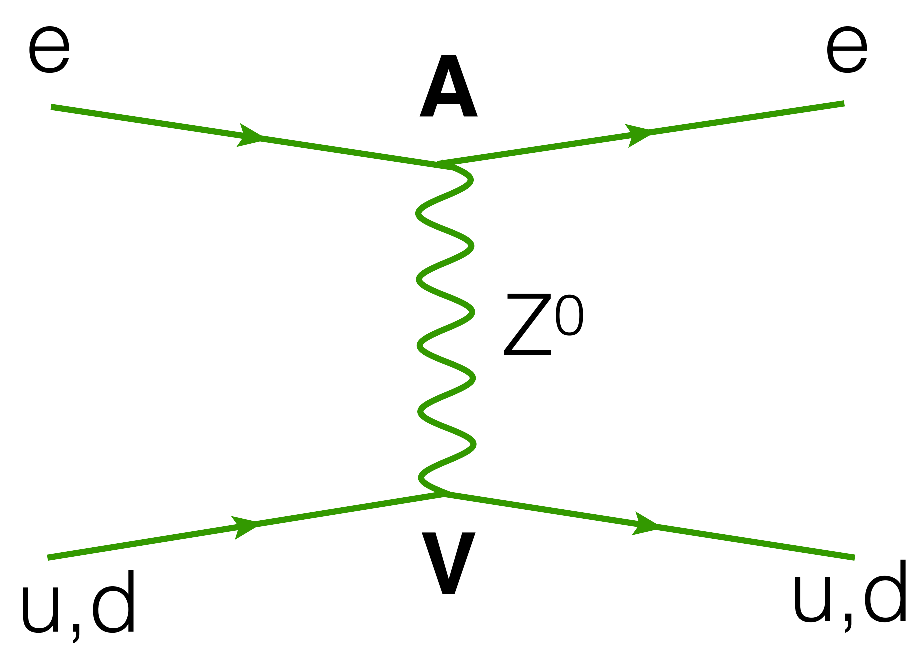
Parity operation:

$$\boldsymbol{\sigma} \to \boldsymbol{\sigma}$$
$$\mathbf{p} \to -\mathbf{p}$$

Atomic parity violation and the nuclear weak charge

Axial vector coupling to electrons,
vector coupling to quarks

$$\frac{G}{\sqrt{2}} C_{1q} \left(\bar{e}\gamma_\mu\gamma_5 e\right)\left(\bar{q}\gamma^\mu q\right)$$



Standard model tree-level couplings

$$C_{1n} = C_{1u} + 2C_{1d} = -\frac{1}{2}$$
$$C_{1p} = 2C_{1u} + C_{1d} = \frac{1}{2}\left(1 - 4\sin^2\theta_W\right)$$

Leads to parity-violating interaction Hamiltonian for electrons

$$h_{\mathrm{PV}} = -\frac{G}{2\sqrt{2}} Q_W \rho(r)\gamma_5$$

where Q_W is *nuclear weak charge.*

SM value known well, $Q_W^{\mathrm{SM}} = -73.23(1)$

Parity-violating nature

Non-relativistic limit:

$$h_{\mathrm{PV}} \propto \boldsymbol{\sigma} \cdot \mathbf{p}$$

Parity operation:

$$\boldsymbol{\sigma} \to \boldsymbol{\sigma}$$
$$\mathbf{p} \to -\mathbf{p}$$

Enhancement with Z

Parity-violating amplitude:

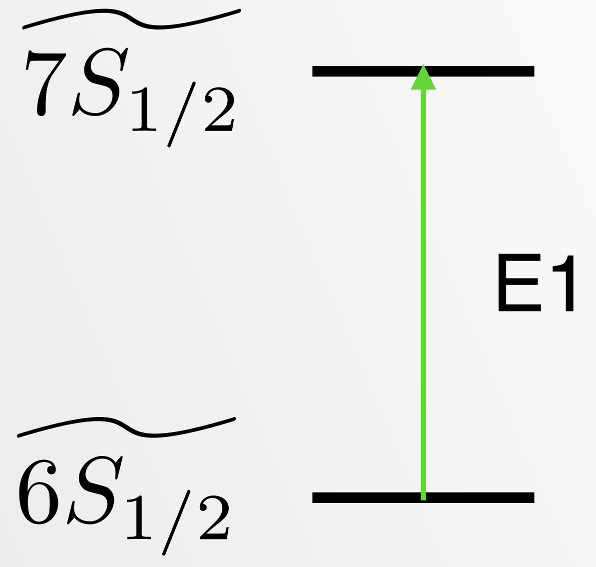
$$E_{\mathrm{PV}} \propto R(Z)Z^3$$

relativistic enhancement factor → $R(Z)$

nuclear charge → Z^3

Bouchiat, Bouchiat (1974)

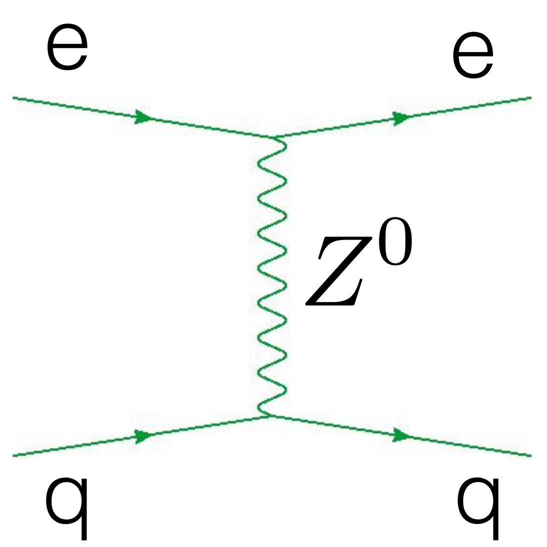
Atomic parity violation in cesium



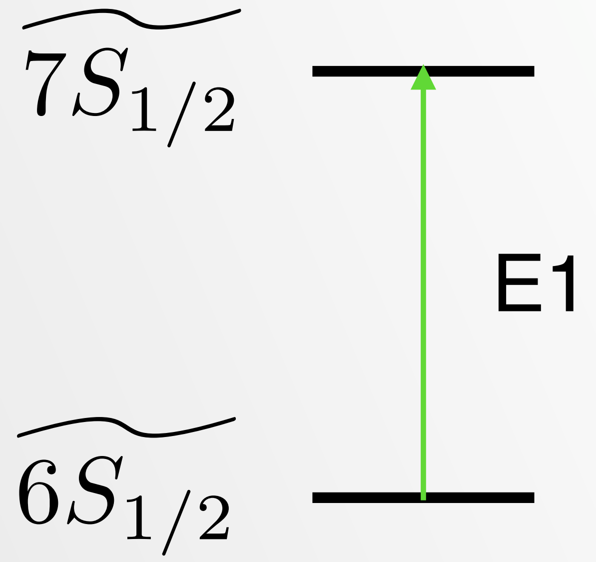
Weak interaction mixes opposite-parity states,

$$|\widetilde{S_{1/2}}\rangle = |S_{1/2}\rangle + \sum_n \frac{\langle nP_{1/2}|H_{\rm PV}|S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} |nP_{1/2}\rangle$$

6S - 7S electric dipole (E1) transition amplitude $E_{\rm PV}$



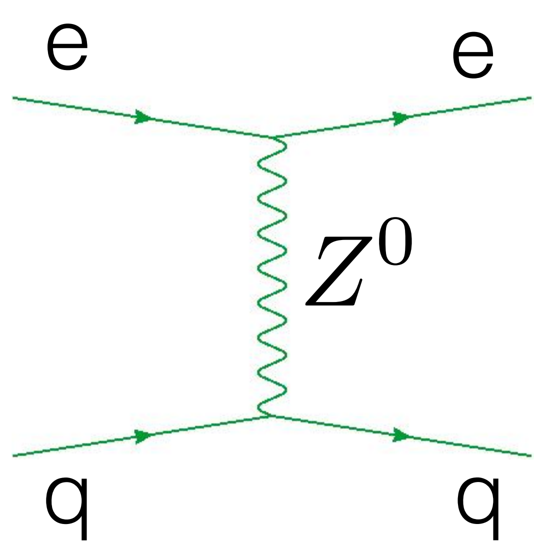
Atomic parity violation in cesium



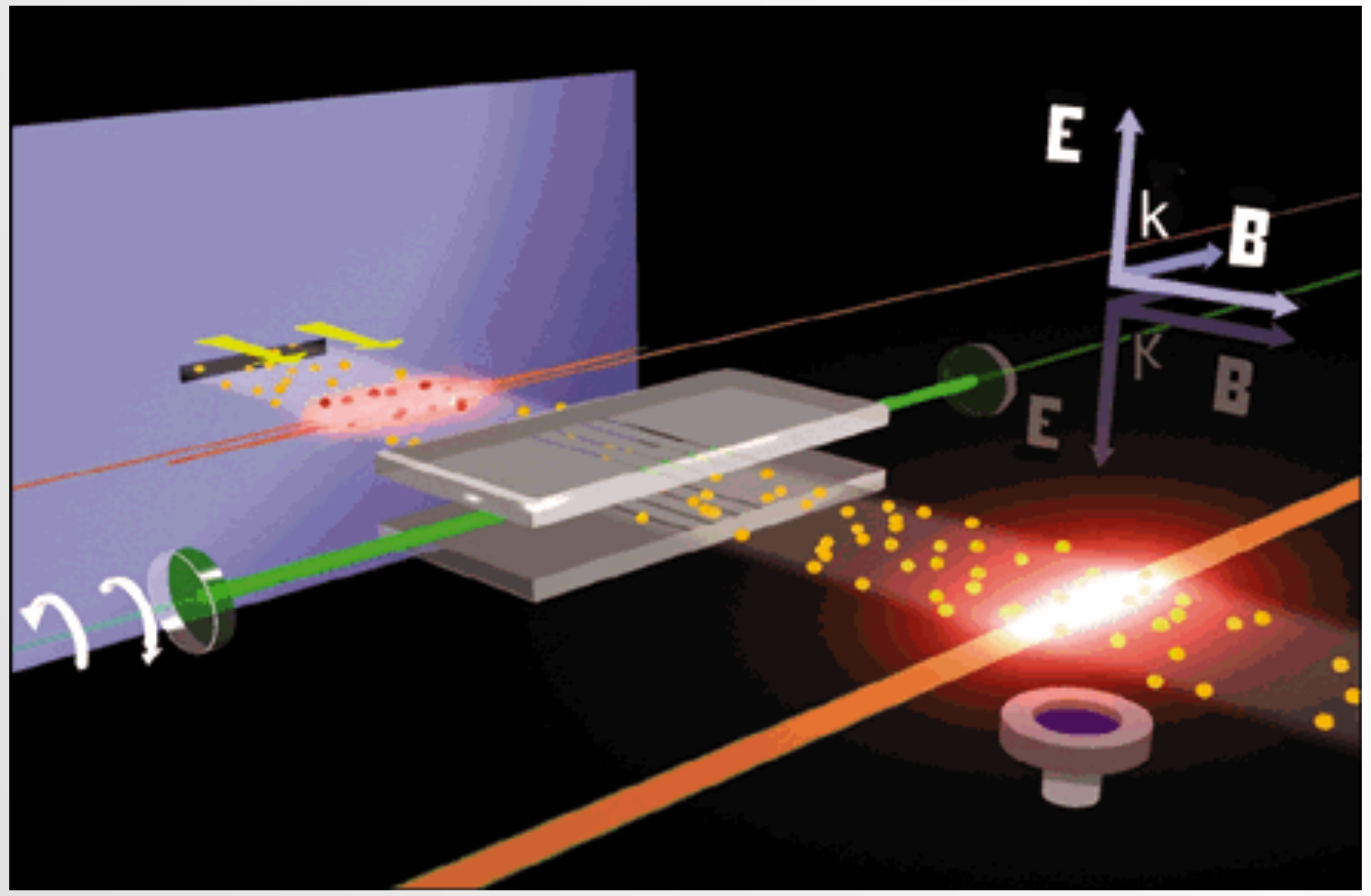
Weak interaction mixes opposite-parity states,

$$|\widetilde{S_{1/2}}\rangle = |S_{1/2}\rangle + \sum_n \frac{\langle nP_{1/2}|H_{\rm PV}|S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} |nP_{1/2}\rangle$$

6S - 7S electric dipole (E1) transition amplitude $E_{\rm PV}$



Experiment, 0.35% uncertainty

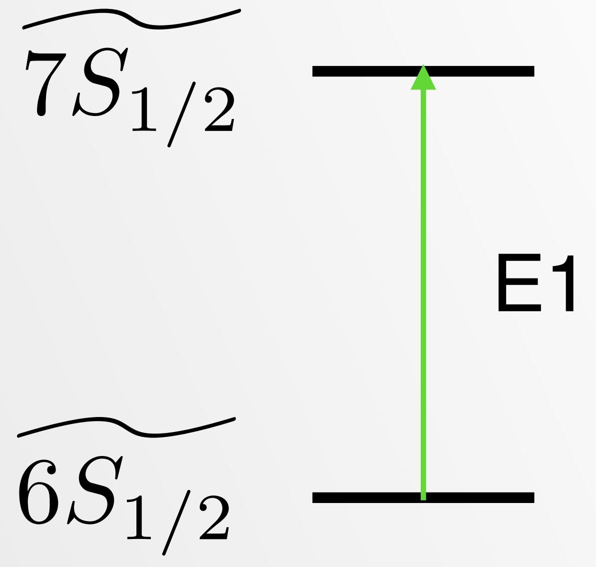


$$-{\rm Im}(E_{\rm PV})/\beta = 1.5935(1 \pm 0.35\%)\,{\rm mV/cm}$$

β – transition polarisability

Carl Wieman group, Wood et al., Science (1997)

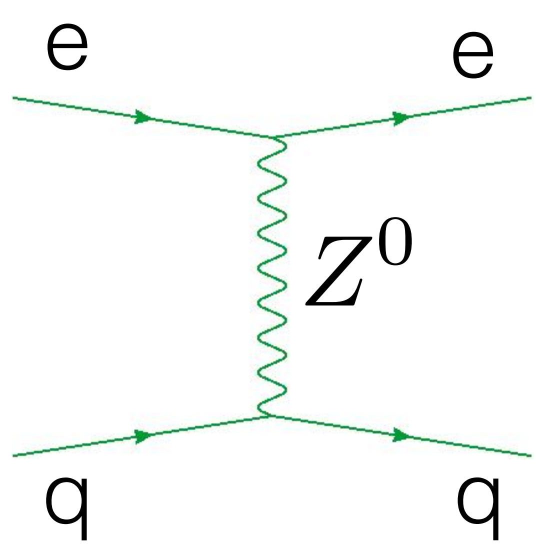
Atomic parity violation in cesium



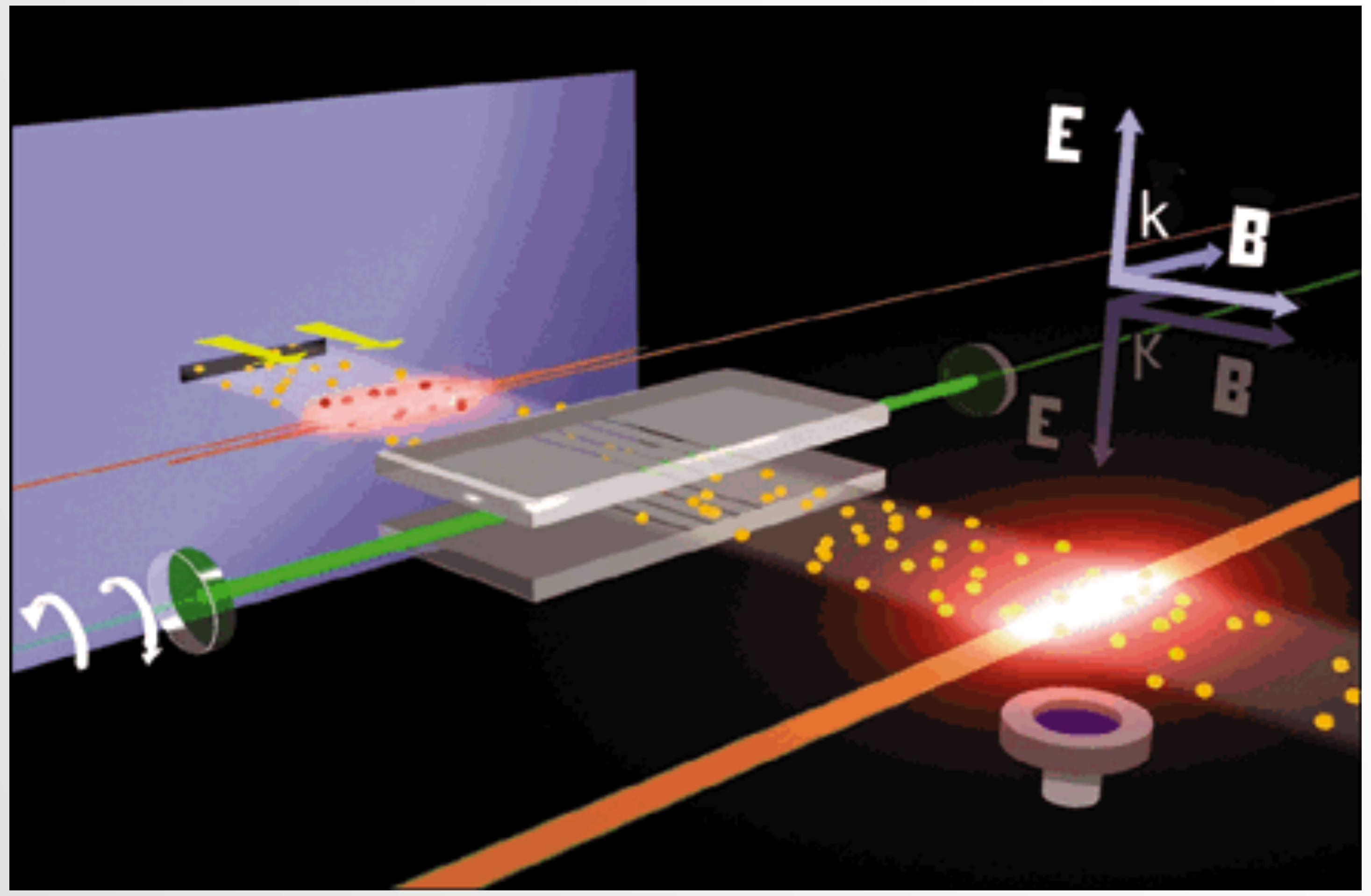
Weak interaction mixes opposite-parity states,

$$|\widetilde{S_{1/2}}\rangle = |S_{1/2}\rangle + \sum_n \frac{\langle nP_{1/2}|H_{\rm PV}|S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} |nP_{1/2}\rangle$$

6S - 7S electric dipole (E1) transition amplitude $E_{\rm PV}$



Experiment, 0.35% uncertainty



$$-{\rm Im}(E_{\rm PV})/\beta = 1.5935(1 \pm 0.35\%)\,{\rm mV/cm}$$

β — transition polarisability

Carl Wieman group, Wood et al., Science (1997)

Atomic theory, 0.5% uncertainty

$$E_{\rm PV} = \langle\widetilde{7S_{1/2}}|D_z|\widetilde{6S_{1/2}}\rangle$$

$$= \sum_n \frac{\langle 7S_{1/2}|D_z|nP_{1/2}\rangle\langle nP_{1/2}|H_{\rm PV}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \ldots$$

$$= \xi\, Q_W$$

Dipole operator: $\mathbf{D} = \sum_i e\mathbf{r}_i$,

Weak operator: $H_{\rm PV} = \sum_i (h_{\rm PV})_i$,

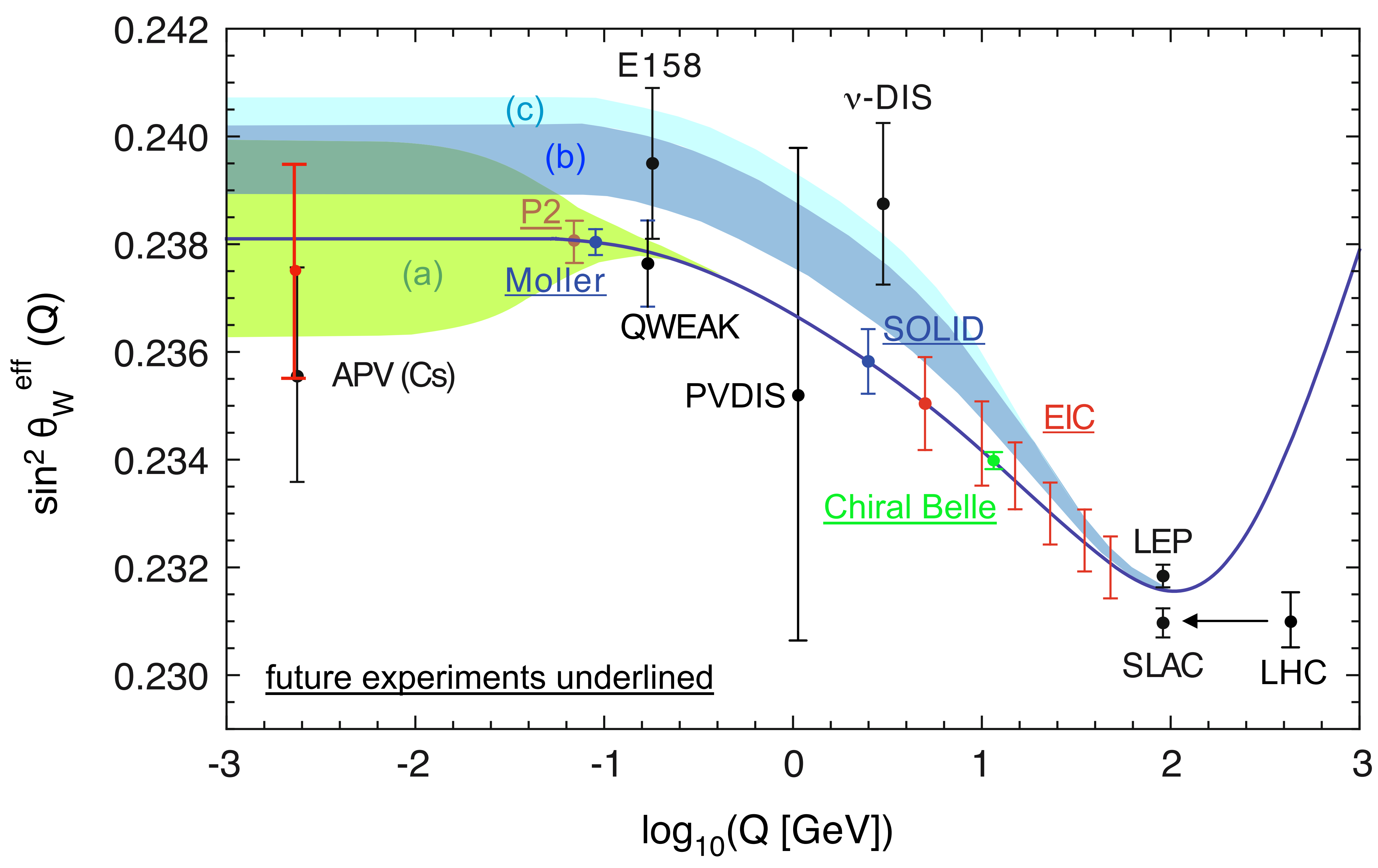
Energies: E

Dzuba, Flambaum, Ginges, PRD (2002); Flambaum, Ginges, PRA (2005)
Porsev, Beloy, Derevianko, PRL (2009); Dzuba, Berengut, Flambaum, Roberts, PRL (2012)

Tests of the standard model

- Experiment and theory: nuclear weak charge: $Q_W = -73.07(28)(33) \quad \Rightarrow \quad Q_W - Q_W^{SM} = 0.16(43)$

Running of the Weinberg angle



QWEAK - electron-proton scattering
E158 - electron-electron scattering @ SLAC
PVDIS - parity-violation in deep inelastic scattering
ν-DIS - neutrino deep inelastic scattering
Tevatron - proton-antiproton collider
LEP - Large Electron Positron collider
SLAC - Stanford Linear Collider, electron-positron collider
LHC - Large Hadron Collider, proton-proton collider

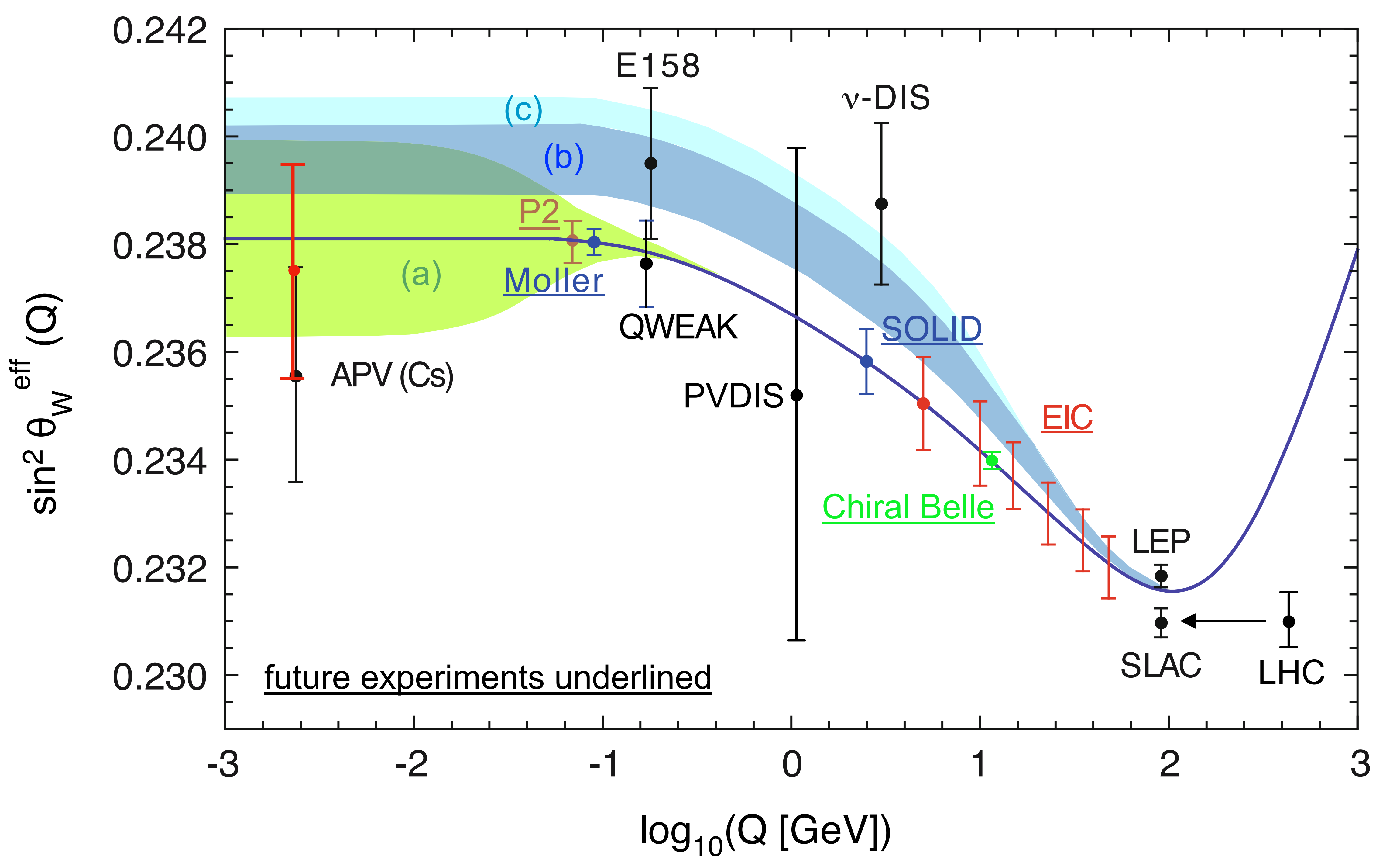
Figure from: Gwinner and Orozco, Quantum Sci. Technol (2022)

New result for vector polarizability shifts APV result (red): G. Toh et al., PRL (2019)

Tests of the standard model

- <u>Experiment and theory</u>: nuclear weak charge: $Q_W = -73.07(28)(33) \quad \Rightarrow \quad Q_W - Q_W^{\rm SM} = 0.16(43)$

Running of the Weinberg angle



QWEAK - electron-proton scattering
E158 - electron-electron scattering @ SLAC
PVDIS - parity-violation in deep inelastic scattering
ν-DIS - neutrino deep inelastic scattering
Tevatron - proton-antiproton collider
LEP - Large Electron Positron collider
SLAC - Stanford Linear Collider, electron-positron collider
LHC - Large Hadron Collider, proton-proton collider

Dark Z boson:
(a) 50 MeV; (b) 15 MeV; (c) 15 MeV, in tension with expt.

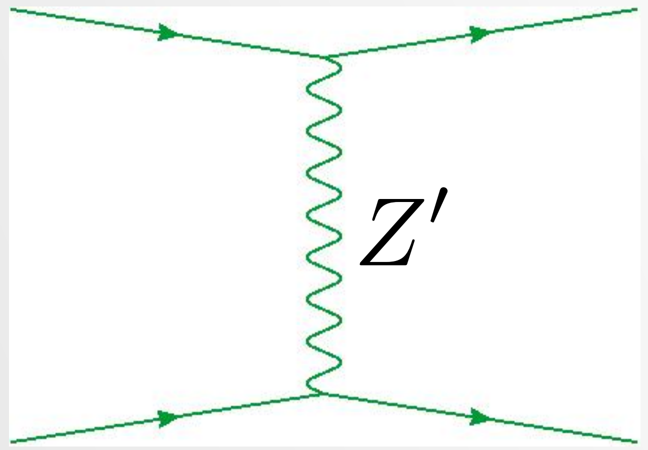
Figure from: Gwinner and Orozco, Quantum Sci. Technol (2022)

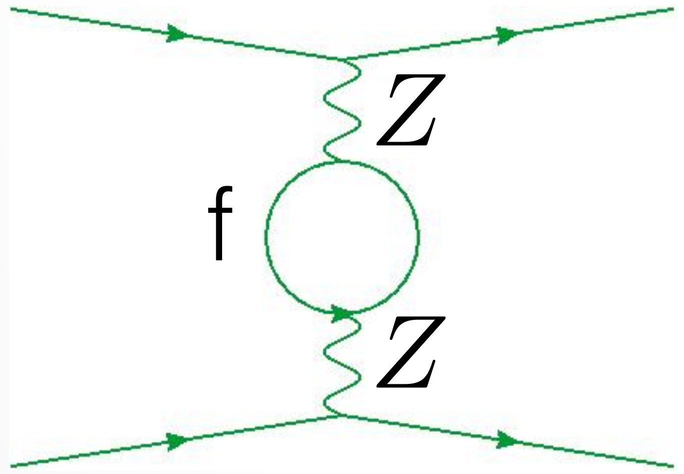
New result for vector polarizability shifts APV result (red): G. Toh et al., PRL (2019)

Searches for new physics

New physics $Q_W = Q_W^{\mathrm{SM}} + \Delta Q_W$

e.g.

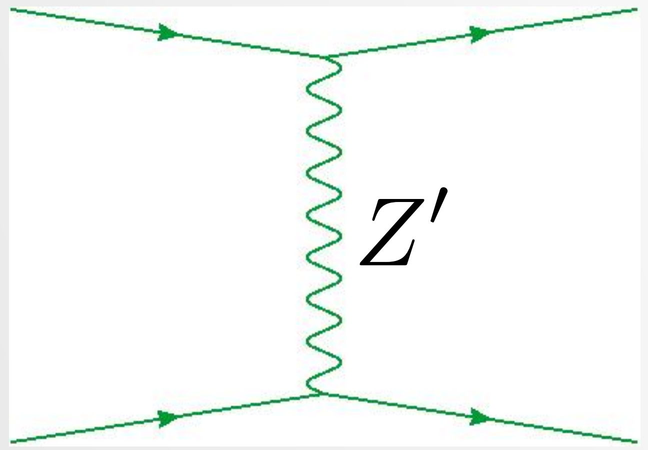


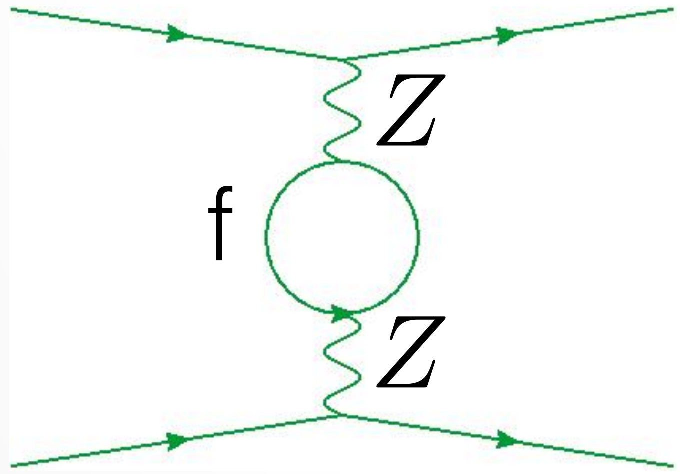


Searches for new physics

New physics $\quad Q_W = Q_W^{\mathrm{SM}} + \Delta Q_W$

e.g.





New tree-level physics. Probing mass scale:

$$\Lambda \geq \left(\frac{8\sqrt{2}\pi\kappa^2}{(\Delta Q_W / Q_W^{\mathrm{SM}})\, G_F} \right)^{1/2}$$

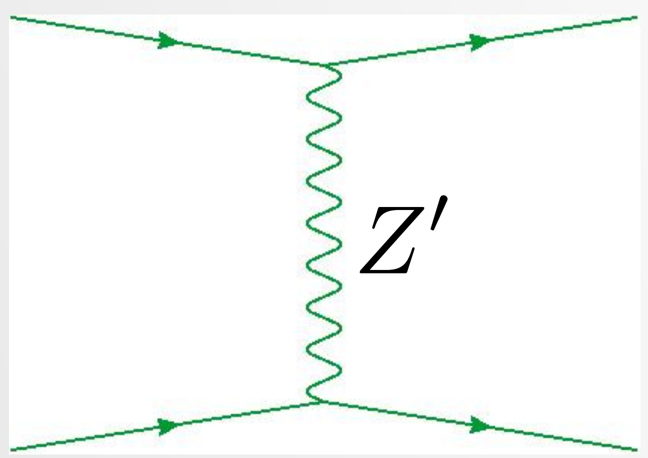
strongly interacting $\kappa^2 \sim 1$, weakly interacting $\kappa^2 \sim \alpha$

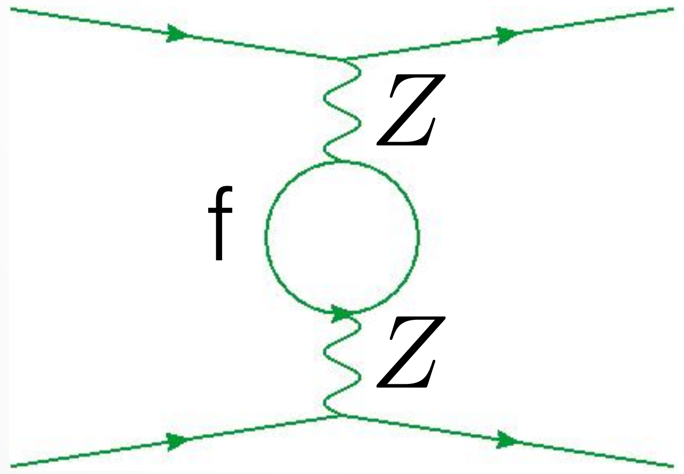
Ramsey-Musolf, PRC (1999)

Searches for new physics

New physics $Q_W = Q_W^{\rm SM} + \Delta Q_W$

e.g.





New tree-level physics. Probing mass scale:

$$\Lambda \geq \left(\frac{8\sqrt{2}\pi\kappa^2}{(\Delta Q_W / Q_W^{\rm SM})\, G_F} \right)^{1/2} \approx 30\kappa \,\text{TeV}$$

for 0.5%

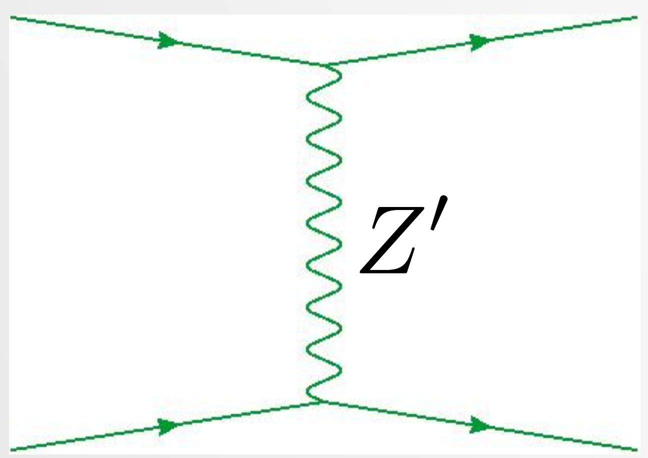
strongly interacting $\kappa^2 \sim 1$, weakly interacting $\kappa^2 \sim \alpha$

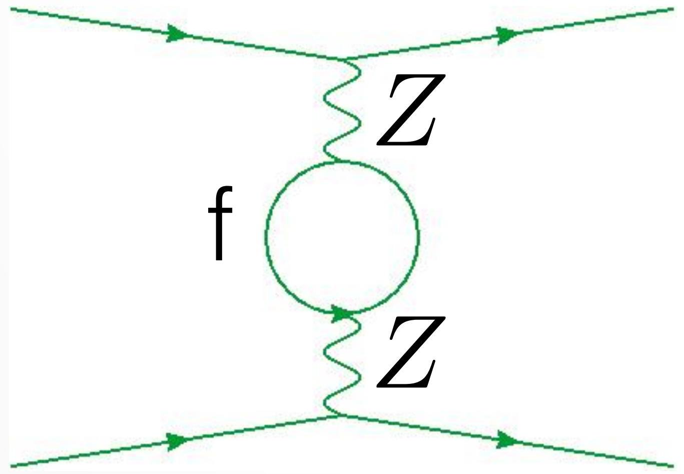
Ramsey-Musolf, PRC (1999)

Searches for new physics

New physics $Q_W = Q_W^{\mathrm{SM}} + \Delta Q_W$

e.g.





New tree-level physics. Probing mass scale:

$$\Lambda \geq \left(\frac{8\sqrt{2}\pi\kappa^2}{(\Delta Q_W / Q_W^{\mathrm{SM}})\, G_F} \right)^{1/2} \approx 30\kappa\,\mathrm{TeV}$$

for 0.5%

strongly interacting $\kappa^2 \sim 1$, weakly interacting $\kappa^2 \sim \alpha$

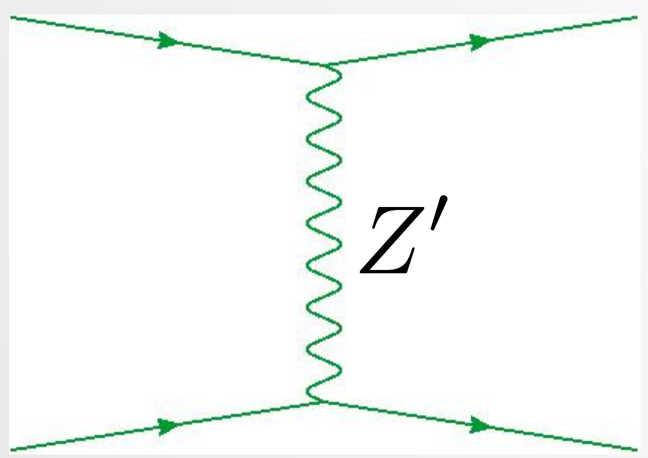
Z' boson: $m_{Z'} \gtrsim 1\,\mathrm{TeV}$

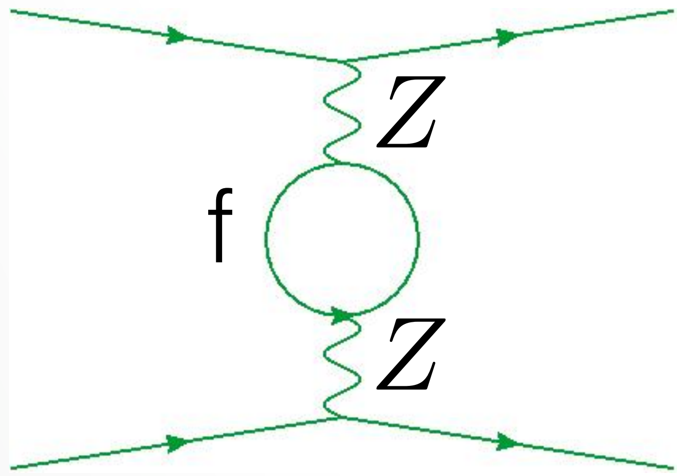
Ramsey-Musolf, PRC (1999)

Searches for new physics

<u>New physics</u> $Q_W = Q_W^{\rm SM} + \Delta Q_W$

e.g.





New tree-level physics. Probing mass scale:

$$\Lambda \geq \left(\frac{8\sqrt{2}\pi\kappa^2}{(\Delta Q_W / Q_W^{\rm SM})\, G_F} \right)^{1/2} \approx 30\kappa\ \mathrm{TeV}$$

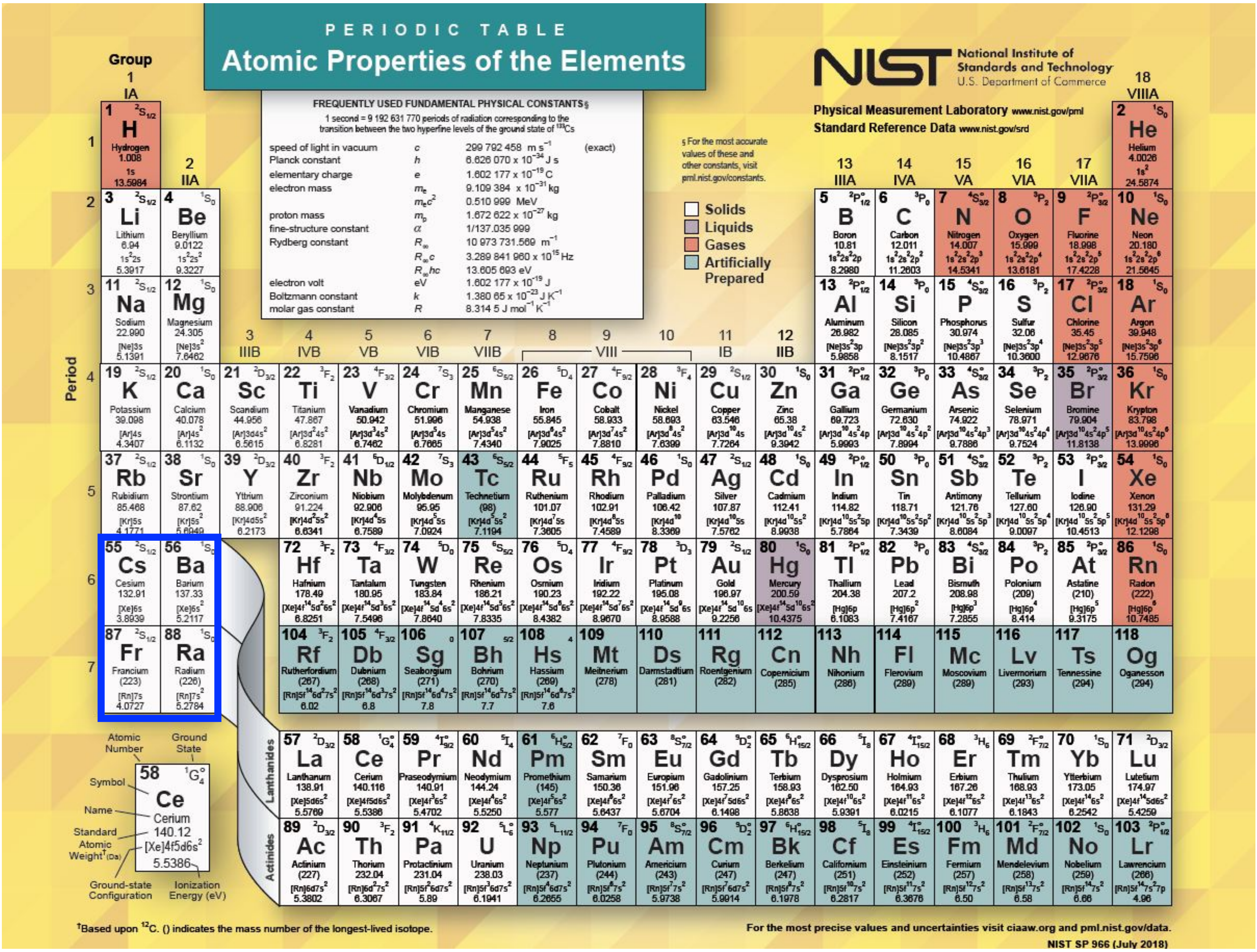
for 0.5%

strongly interacting $\kappa^2 \sim 1$, weakly interacting $\kappa^2 \sim \alpha$

Z' boson: $m_{Z'} \gtrsim 1\,\mathrm{TeV}$

Ramsey-Musolf, PRC (1999)

Experiments in preparation/progress



Neutral atoms: Cs (Purdue) ; Fr (TRIUMF; Tokyo)

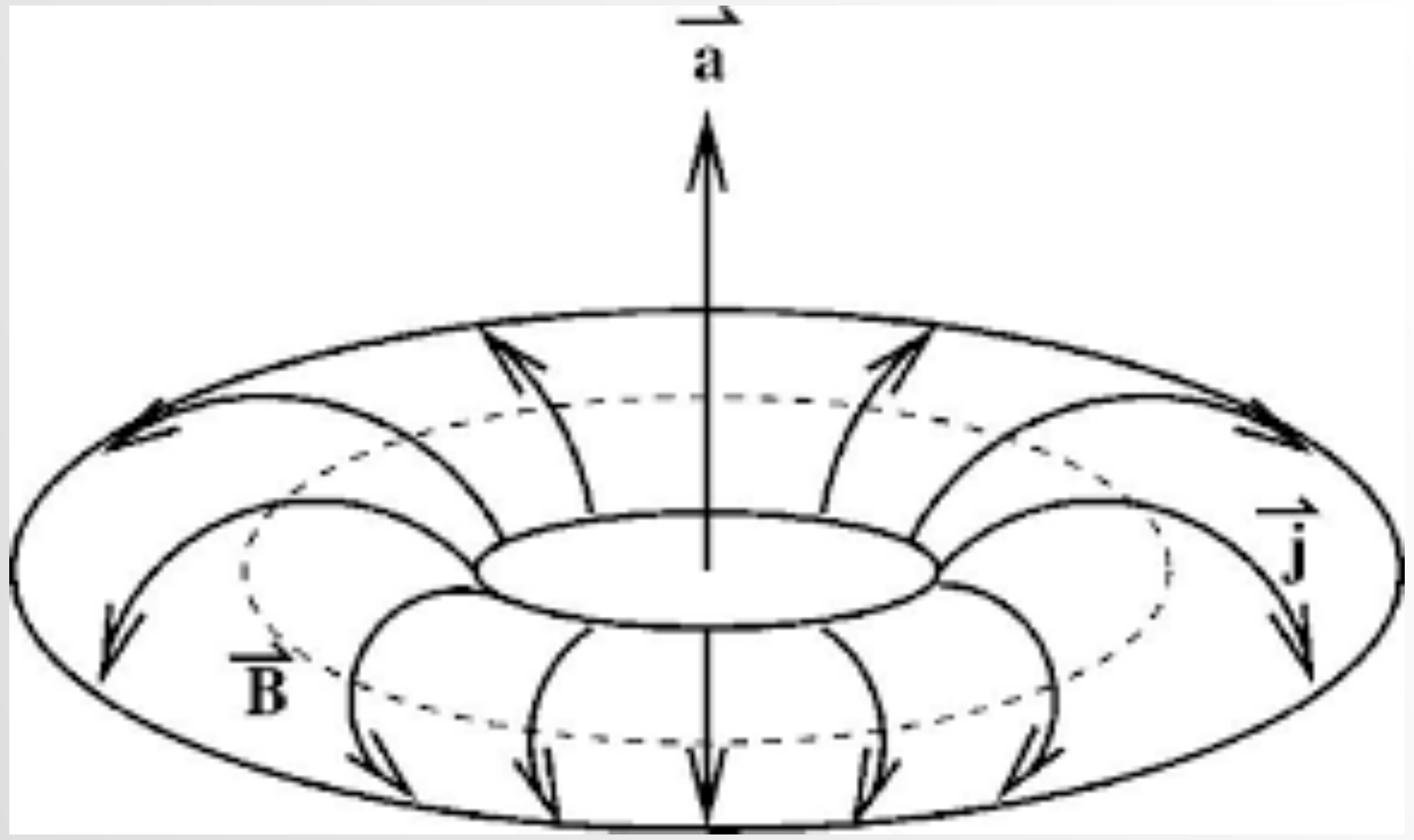
Singly-ionized atoms: Ba+ (Seattle) ; Ra+ (Groningen)

Nuclear-spin-dependent

- from C_{2q}, Z-boson axial vector coupling to quarks and vector coupling to electrons:

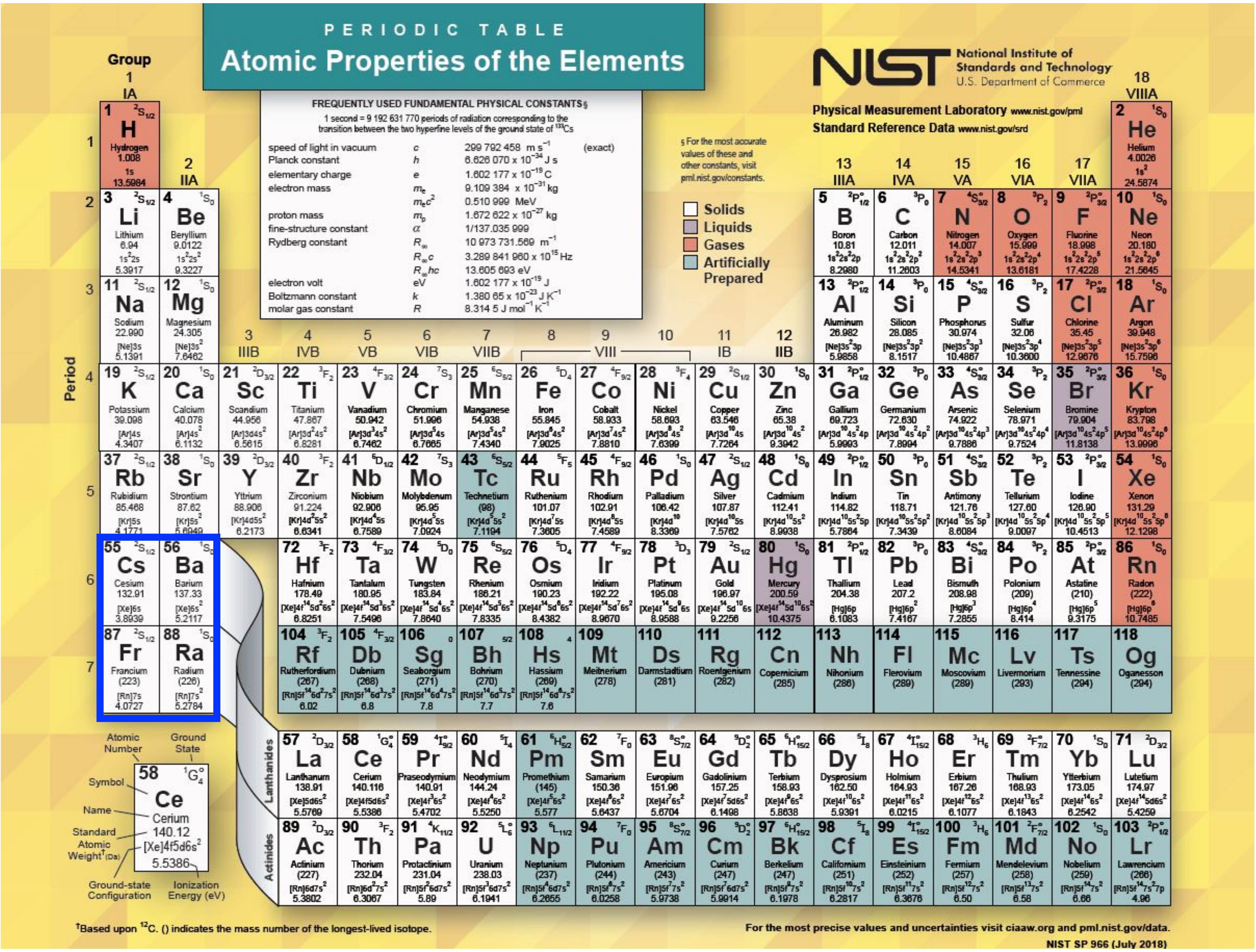
  $\Rightarrow$ *nuclear-spin-dependent* effects in atoms

- Dominated by another effect: *nuclear anapole moment*, produced from parity-violating nuclear forces



Haxton and Wieman, Ann. Rev. Nuc. Part. Sci. (2001)
Flambaum and Ginges, Phys. Rep. (2004)

Experiments in preparation/progress



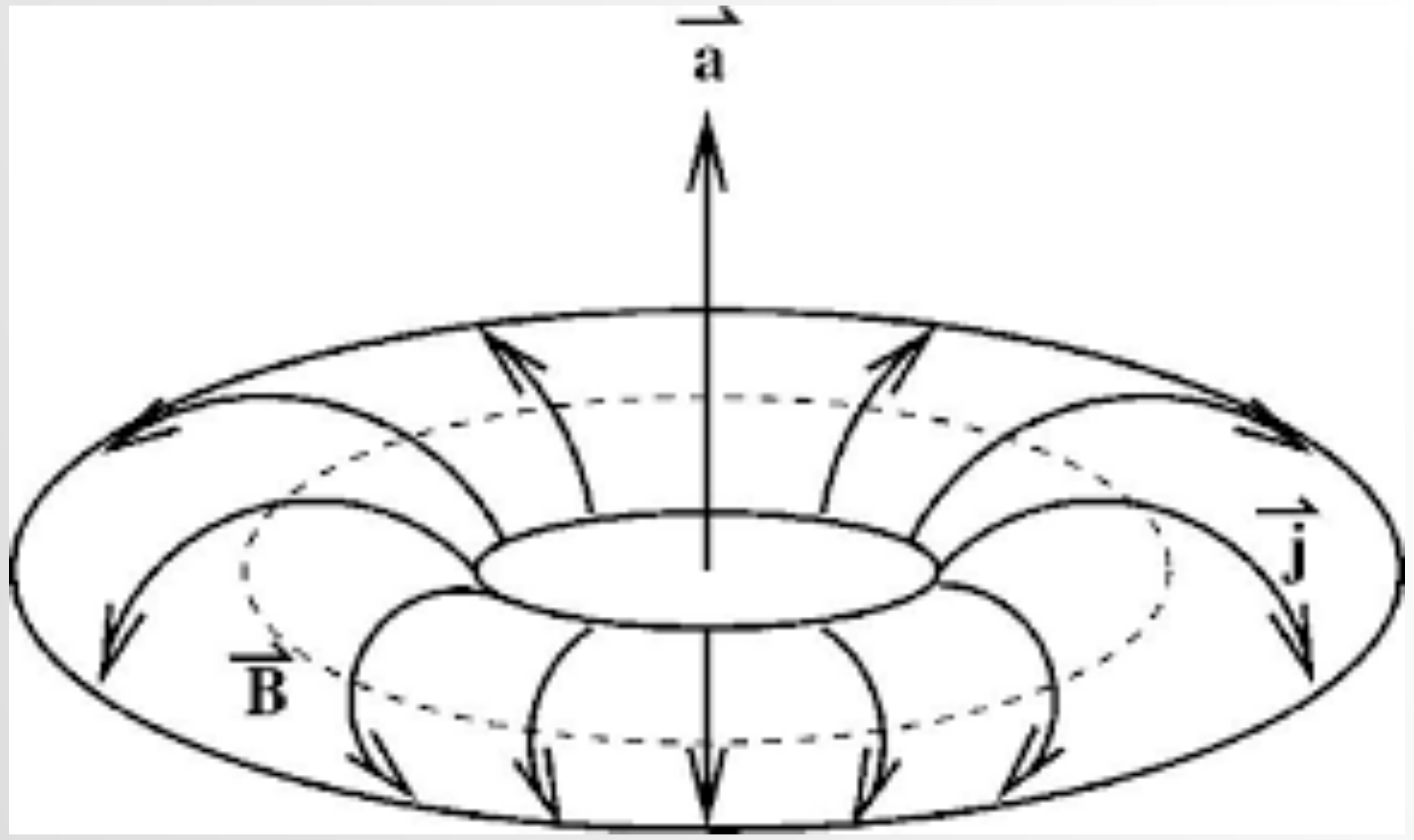
Neutral atoms: Cs (Purdue) ; Fr (TRIUMF; Tokyo)
Singly-ionized atoms: Ba^{+} (Seattle) ; Ra^{+} (Groningen)

Nuclear-spin-dependent

- from C_{2q}, Z-boson axial vector coupling to quarks and vector coupling to electrons:

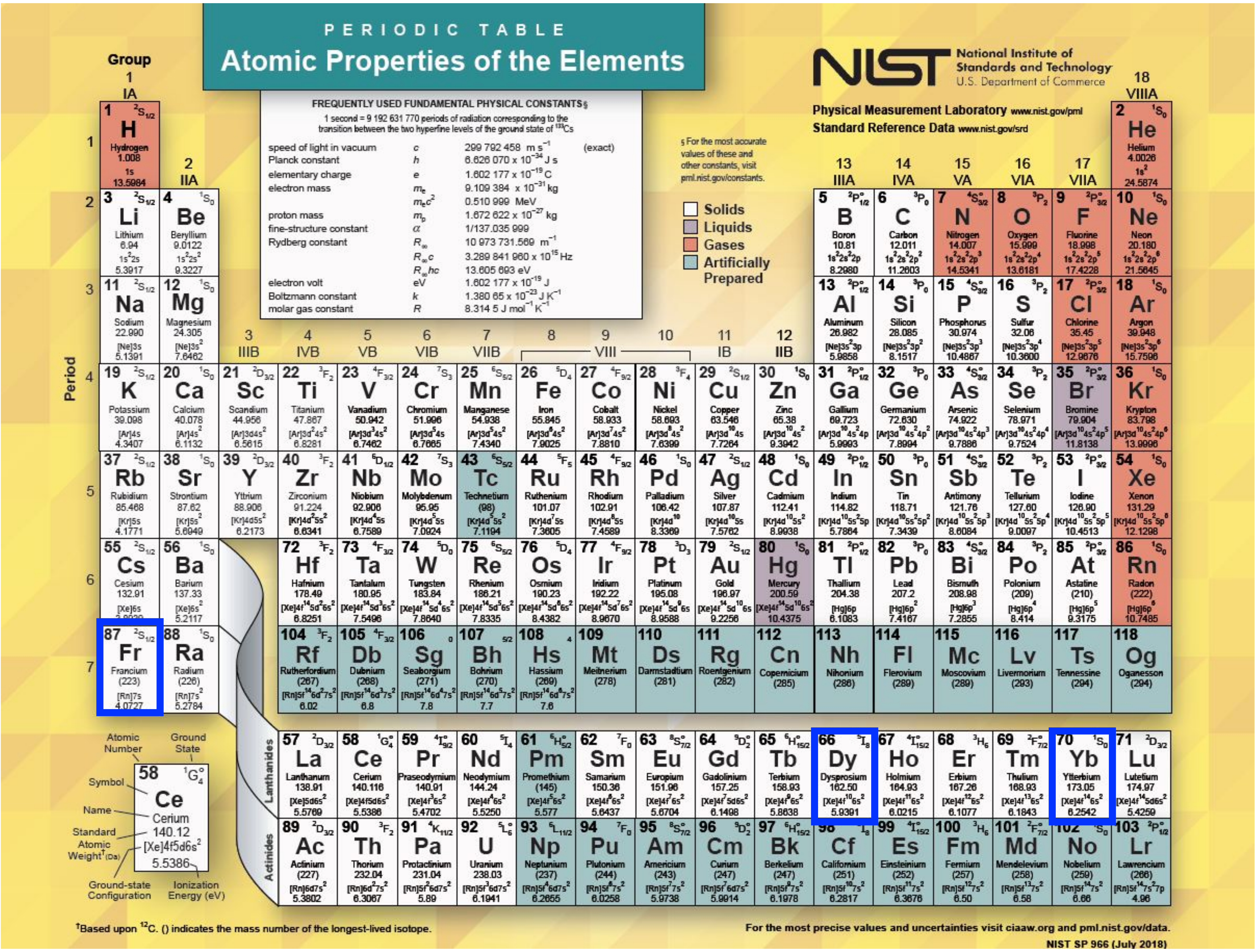
  $\Rightarrow$ *nuclear-spin-dependent* effects in atoms

- Dominated by another effect: *nuclear anapole moment*, produced from parity-violating nuclear forces



Haxton and Wieman, Ann. Rev. Nuc. Part. Sci. (2001)
Flambaum and Ginges, Phys. Rep. (2004)

Experiments in preparation/progress



Also APV along an isotope chain! Remove dependence on atomic theory

Budker group, Mainz: Yb, Dy. D. Antypas et al., Nature Physics (2019)

FrPNC collaboration: Fr

Overview

Testing the SM and searching for new physics in atoms

- Atomic parity violation
- Time-reversal-violating electric dipole moments

Adventures at the intersection of atomic and nuclear physics

- Case study in the hyperfine structure

Our precision atomic theory group at UQ — goal

To maximise the discovery potential of precision atomic experiments

- Push state-of-the-art atomic calculations to 0.1% precision
  - Development of high-precision many-body methods
  - Improved benchmarking of atomic theory

Our precision atomic theory group at UQ — goal

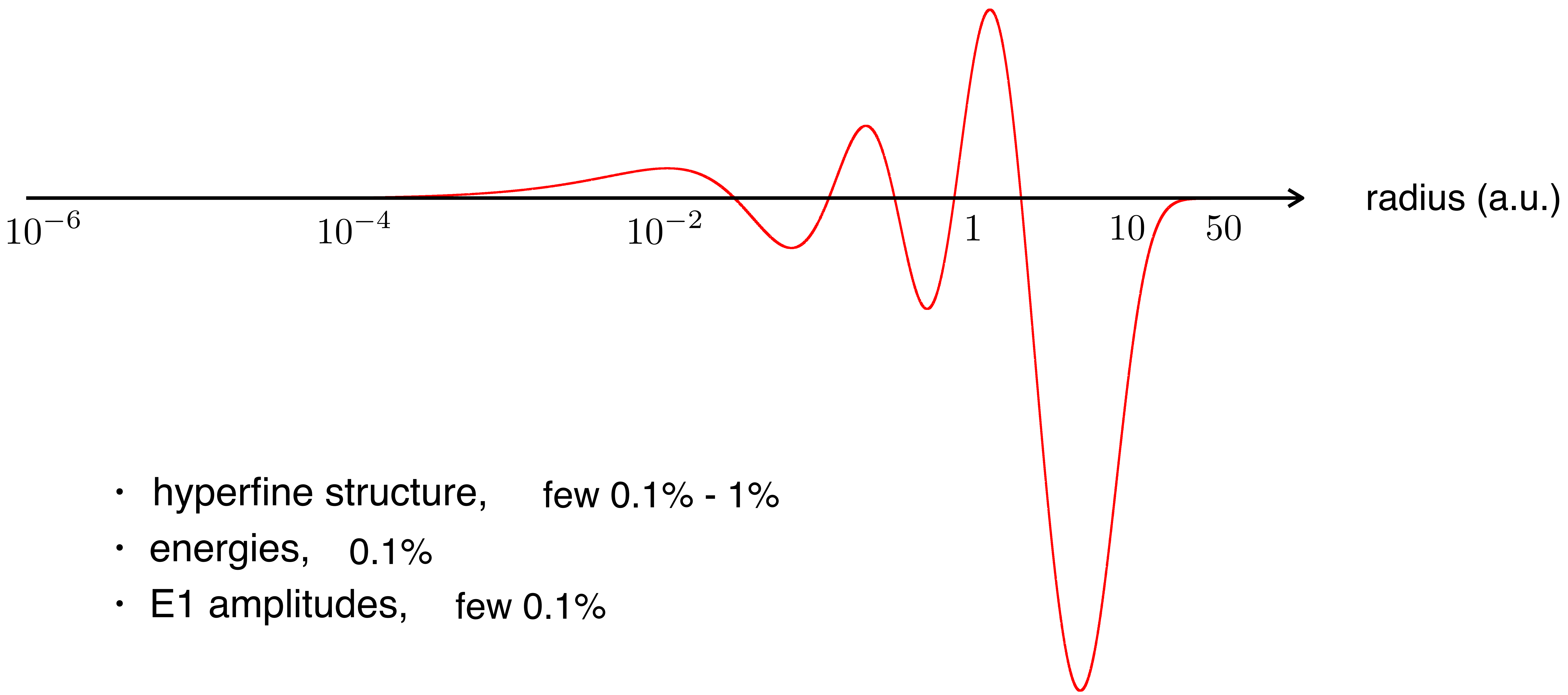
To maximise the discovery potential of precision atomic experiments

- ➤ Push state-of-the-art atomic calculations to 0.1% precision
  - ➤ Development of high-precision many-body methods
  - ➤ Improved benchmarking of atomic theory

Remove nuclear structure uncertainties that hinder tests of atomic theory

Benchmarking atomic theory

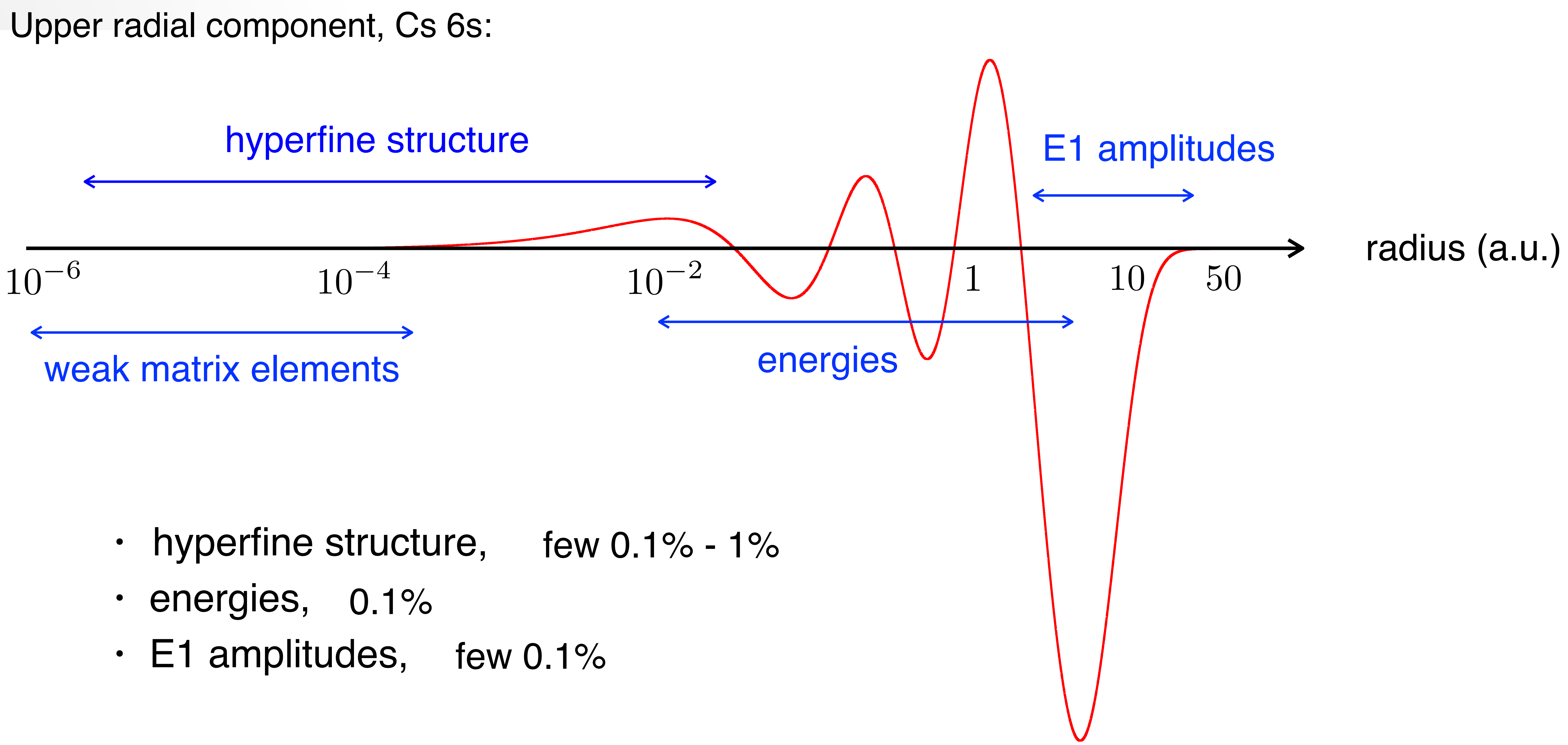
Upper radial component, Cs 6s:



- hyperfine structure, few 0.1% - 1%
- energies, 0.1%
- E1 amplitudes, few 0.1%

$$E_{\rm PV} = \sum_n \frac{\langle 7S_{1/2}|D|nP_{1/2}\rangle\langle nP_{1/2}|H_{\rm PV}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2}|H_{\rm PV}|nP_{1/2}\rangle\langle nP_{1/2}|D|6S_{1/2}\rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

Benchmarking atomic theory

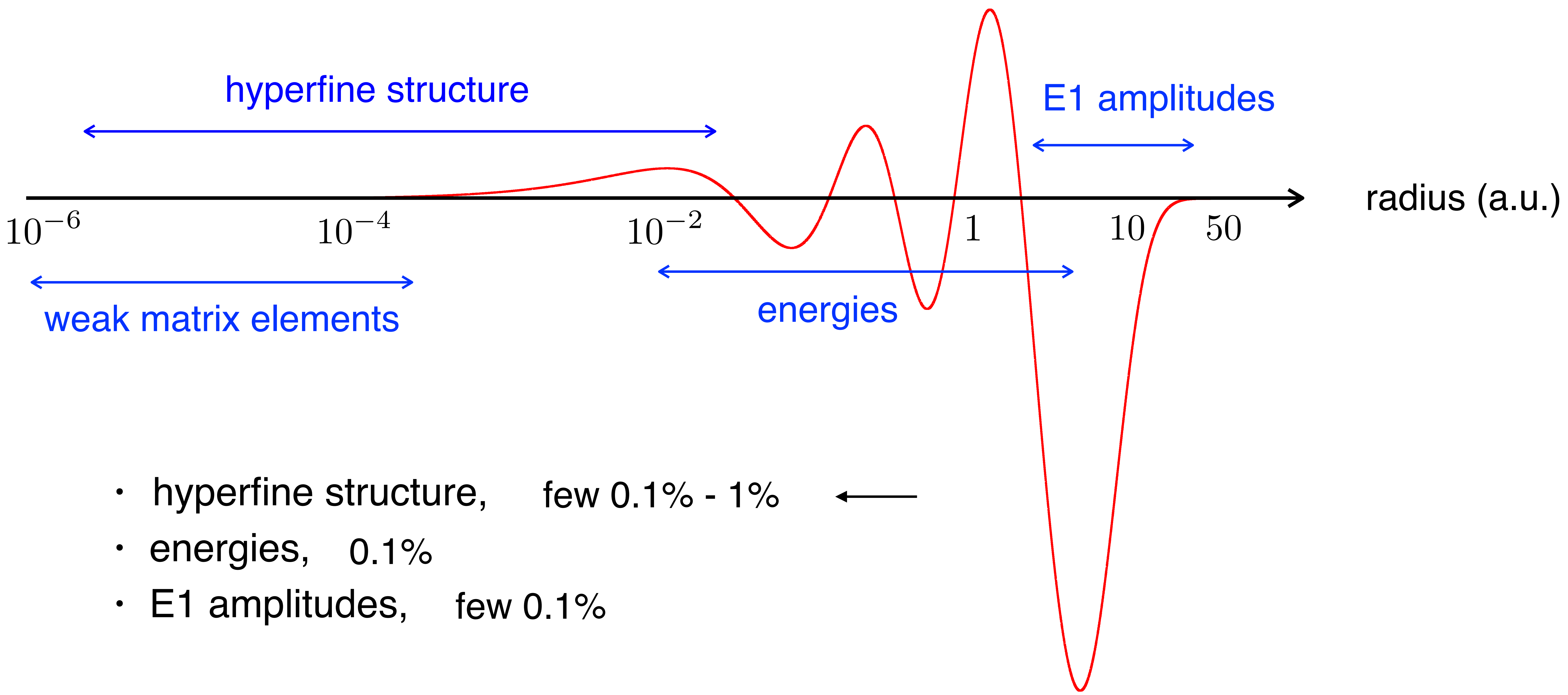


- hyperfine structure, few 0.1% - 1%
- energies, 0.1%
- E1 amplitudes, few 0.1%

$$E_{\rm PV} = \sum_n \frac{\langle 7S_{1/2}|D|nP_{1/2}\rangle\langle nP_{1/2}|H_{\rm PV}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2}|H_{\rm PV}|nP_{1/2}\rangle\langle nP_{1/2}|D|6S_{1/2}\rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

Benchmarking atomic theory

Upper radial component, Cs 6s:



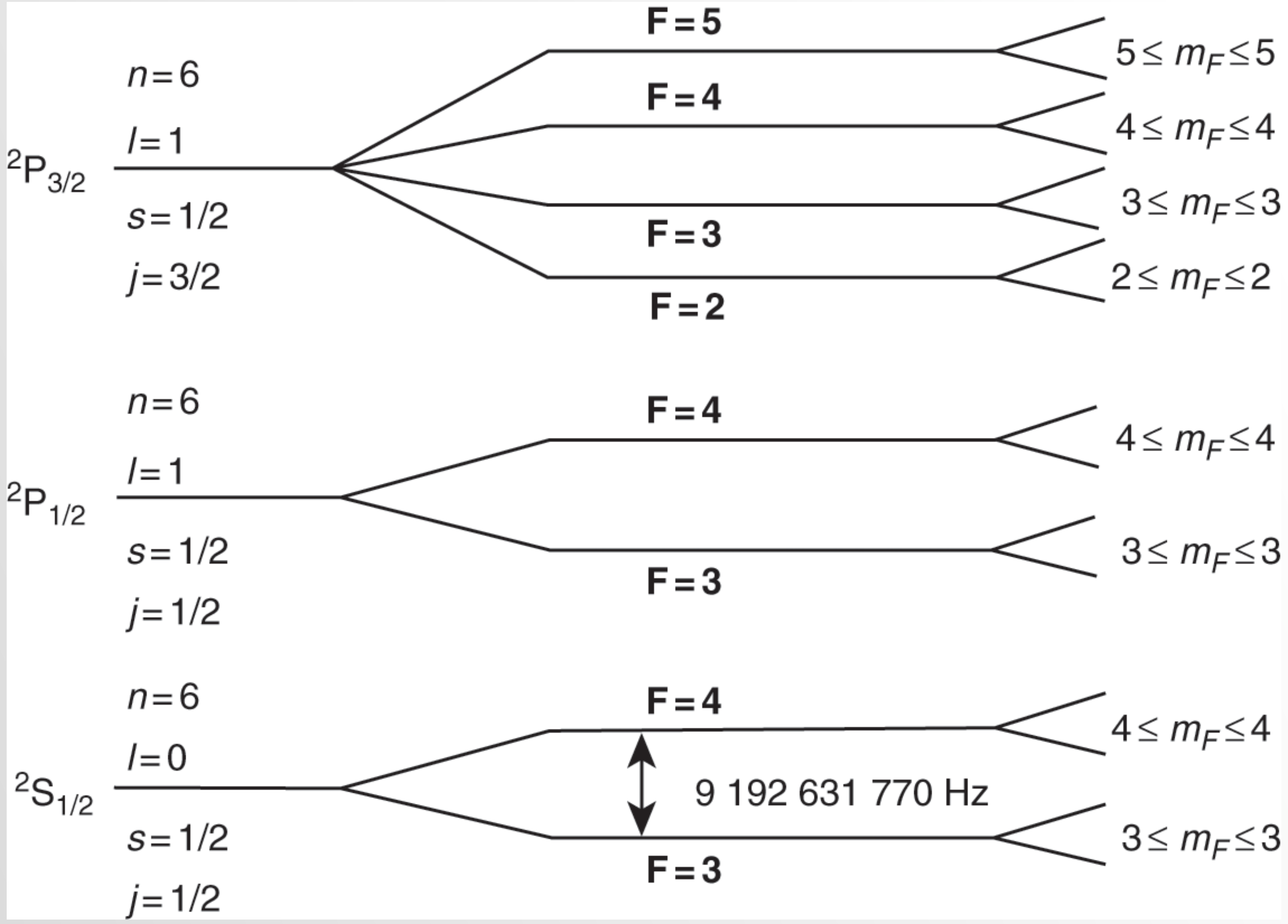
- hyperfine structure, few 0.1% - 1% ⟵
- energies, 0.1%
- E1 amplitudes, few 0.1%

$$E_{\rm PV} = \sum_n \frac{\langle 7S_{1/2}|D|nP_{1/2}\rangle\langle nP_{1/2}|H_{\rm PV}|6S_{1/2}\rangle}{E_{6S_{1/2}} - E_{nP_{1/2}}} + \sum_n \frac{\langle 7S_{1/2}|H_{\rm PV}|nP_{1/2}\rangle\langle nP_{1/2}|D|6S_{1/2}\rangle}{E_{7S_{1/2}} - E_{nP_{1/2}}} = \xi Q_W$$

Fine and hyperfine structure

Fine and hyperfine splitting of levels in ^{133}Cs

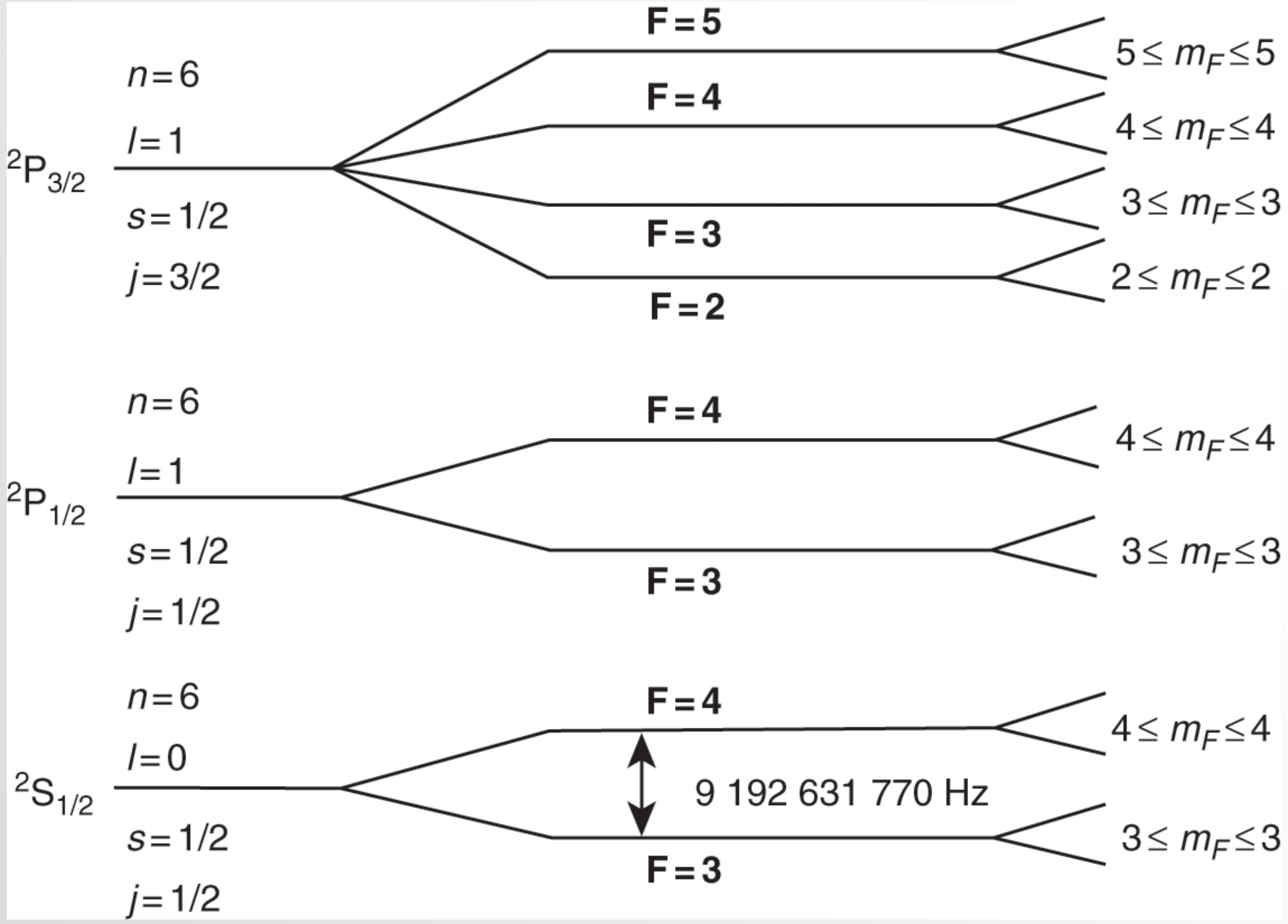
Nuclear spin $I = (7/2)^{+}$,
total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{J}$

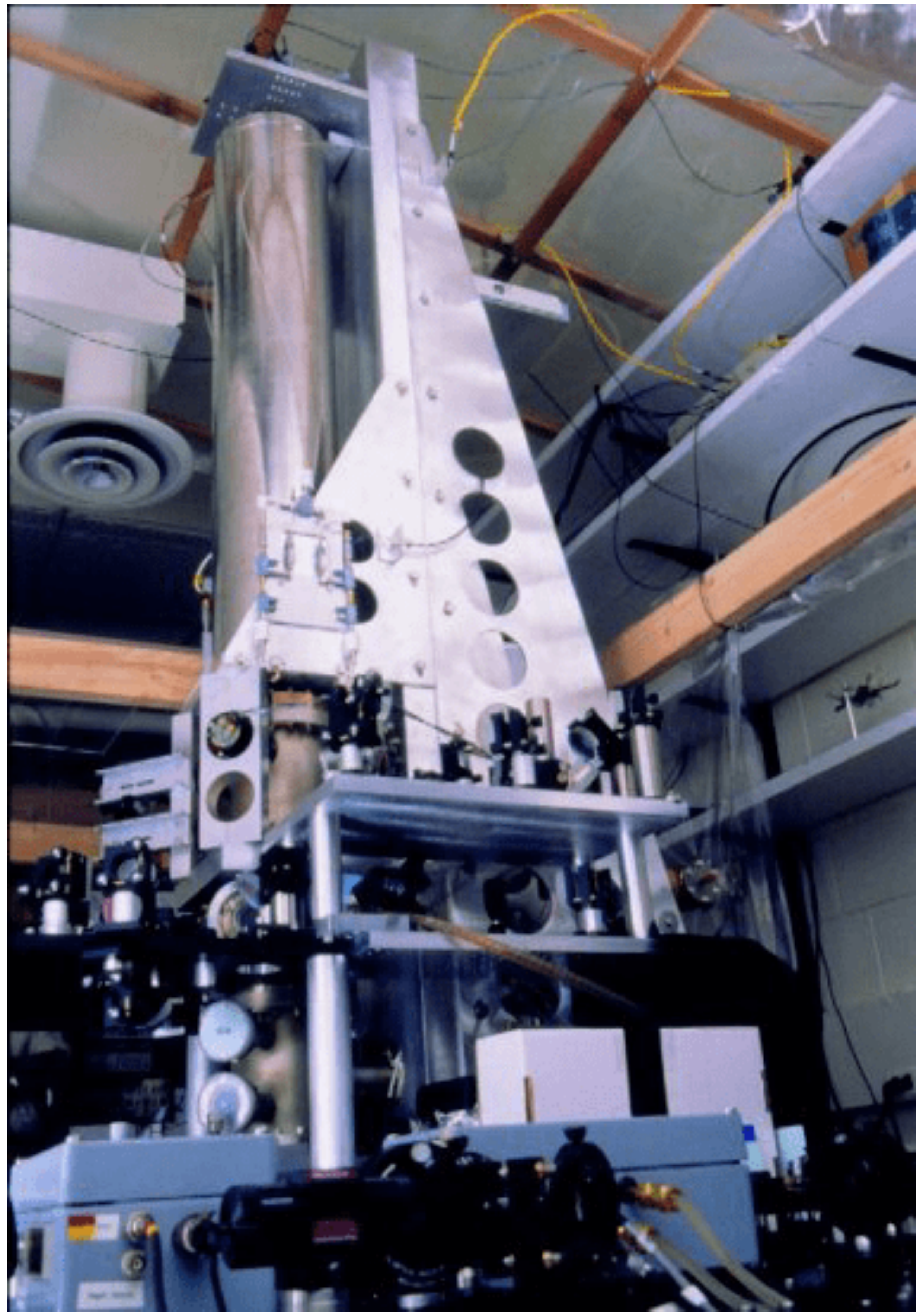


Fine and hyperfine structure

Fine and hyperfine splitting of levels in ^{133}Cs

Nuclear spin $I = (7/2)^{+}$,
total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{J}$

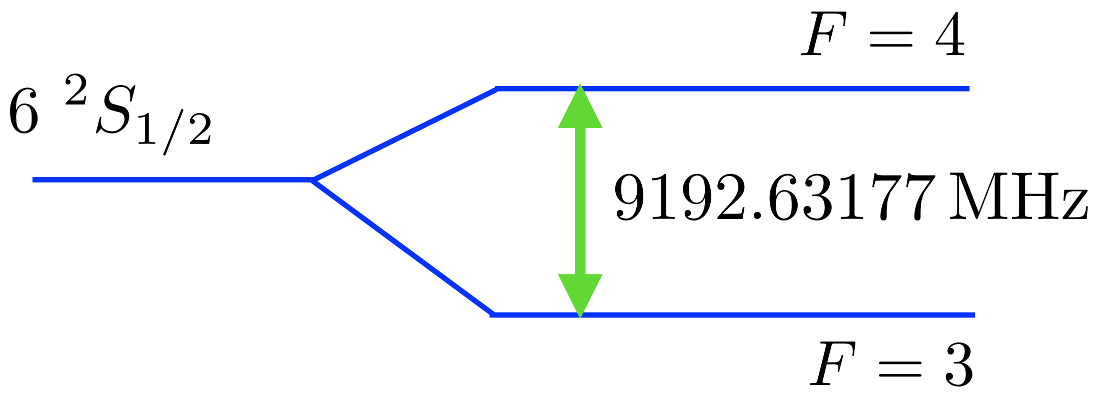




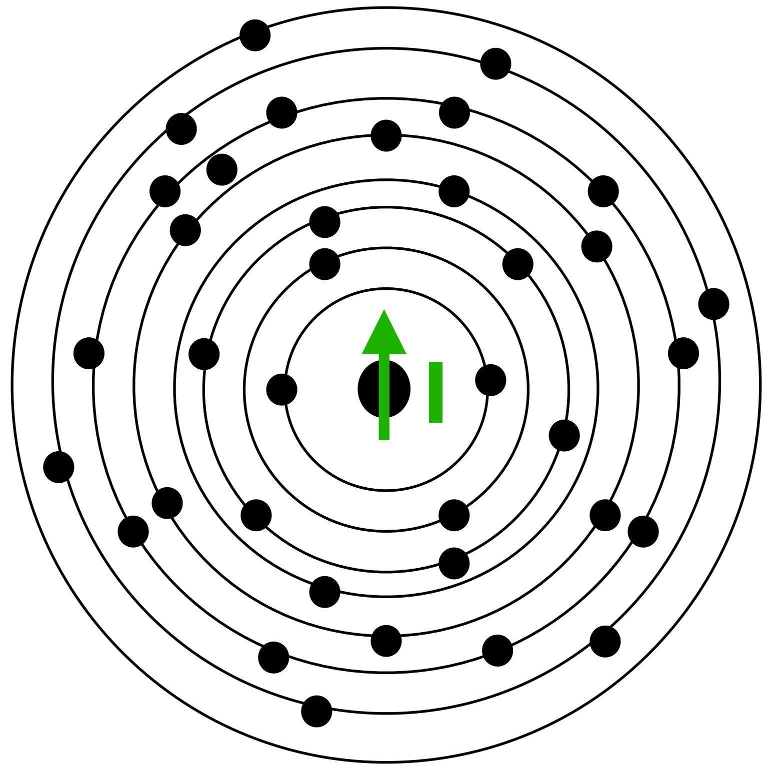
NIST-F2 Atomic clock

Primary standard for the SI unit for time, the *second*

Hyperfine splitting in cesium

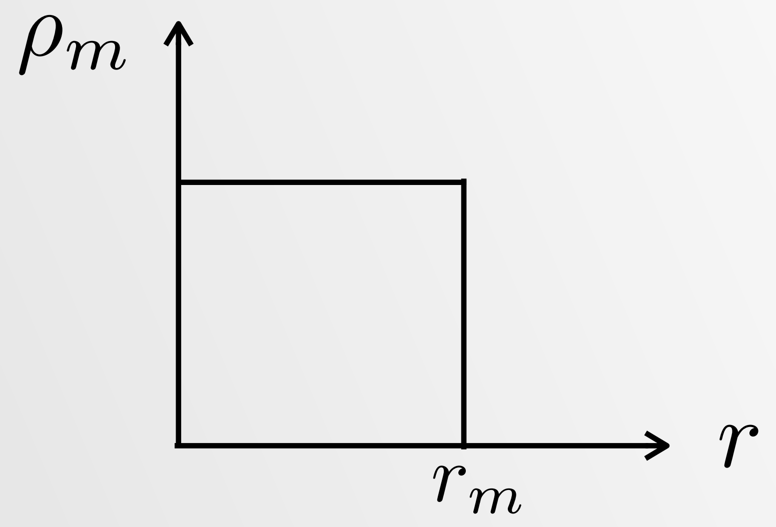


Modeling the hyperfine structure

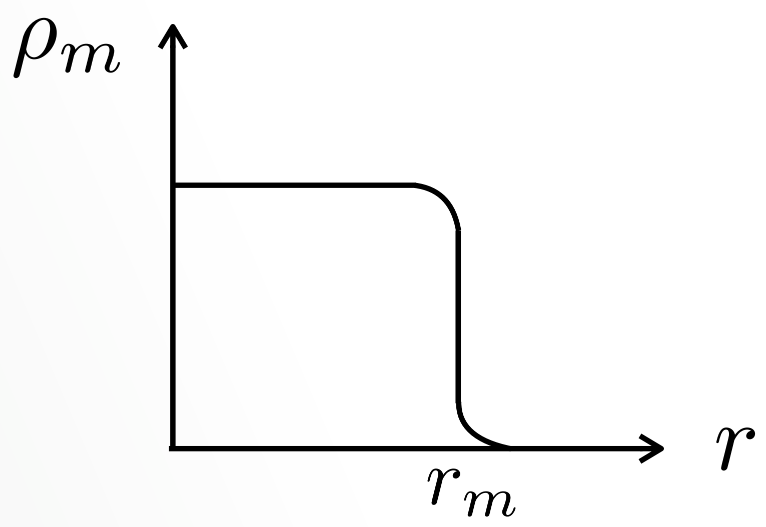


Interaction $h_{\mathrm{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$

Ball, $F(r) = (r/r_m)^3$



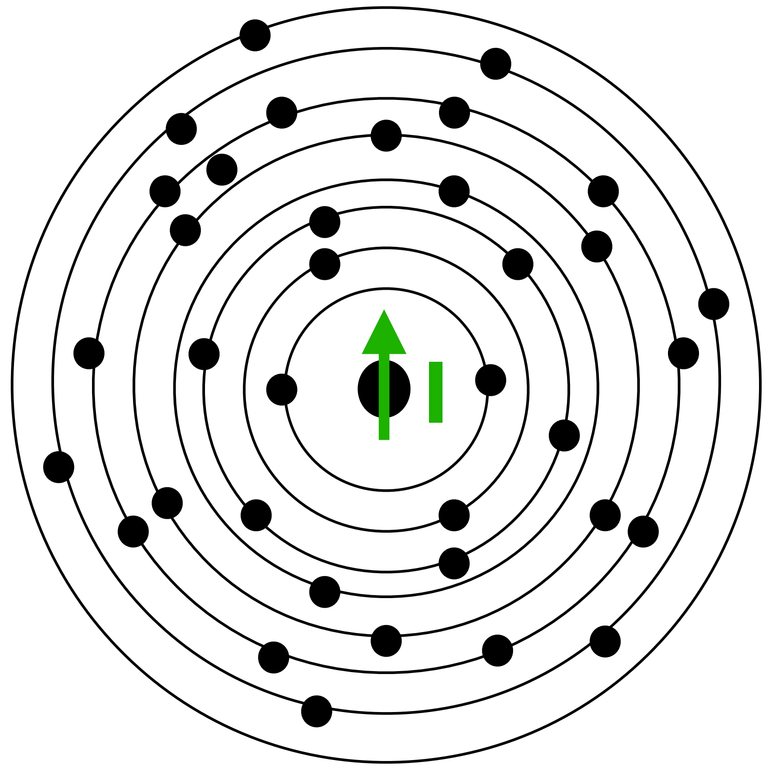
Fermi distribution



Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A,* $A = A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$

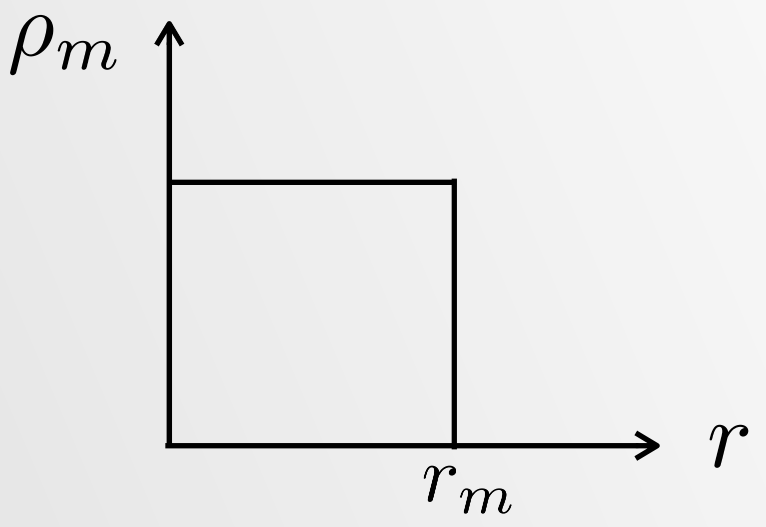
Modeling the hyperfine structure



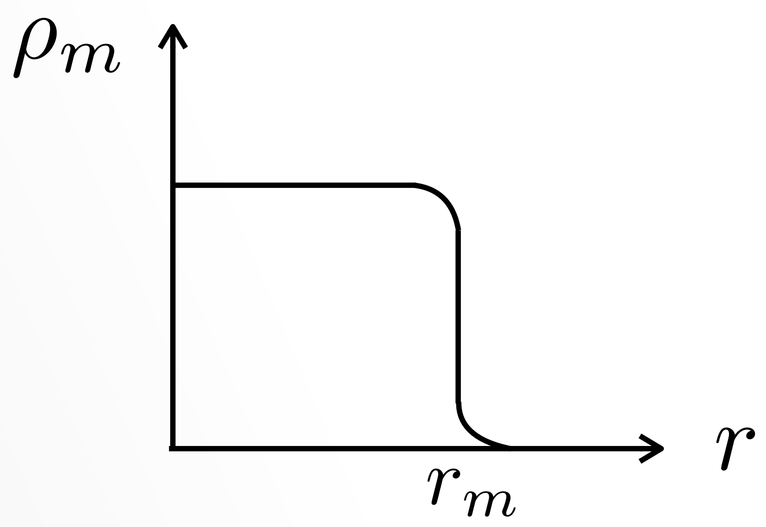
nuclear magnetic moment $\boldsymbol{\mu} = \mu \mathbf{I}/I$

Interaction $h_{\rm hfs} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$

Ball, $F(r) = (r/r_m)^3$



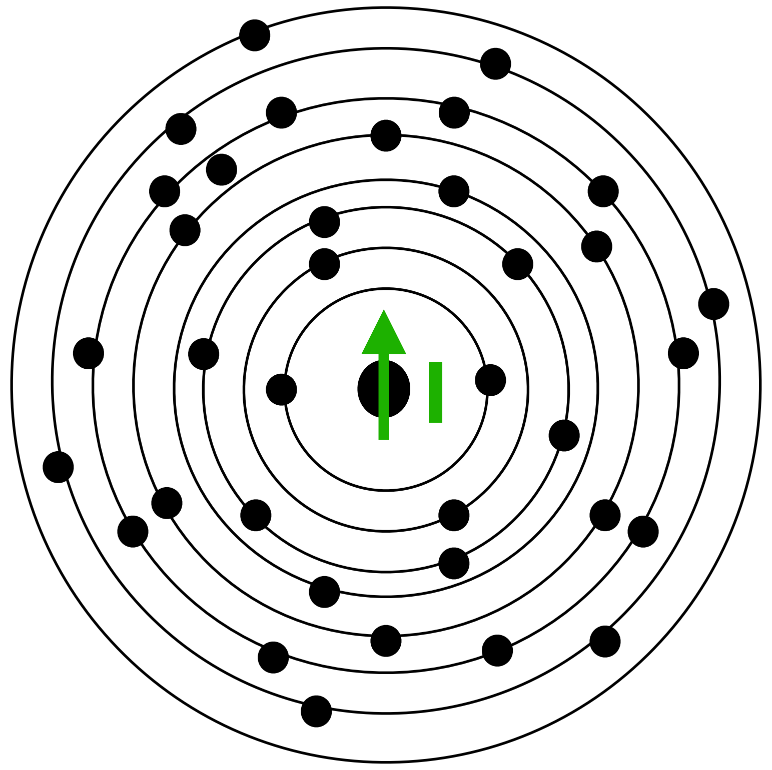
Fermi distribution



Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\rm QED}$

Modeling the hyperfine structure

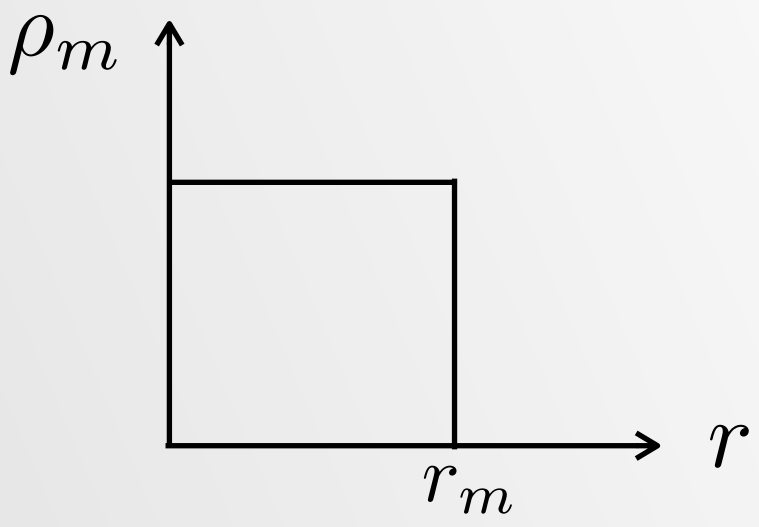


nuclear magnetic moment $\boldsymbol{\mu} = \mu \mathbf{I}/I$

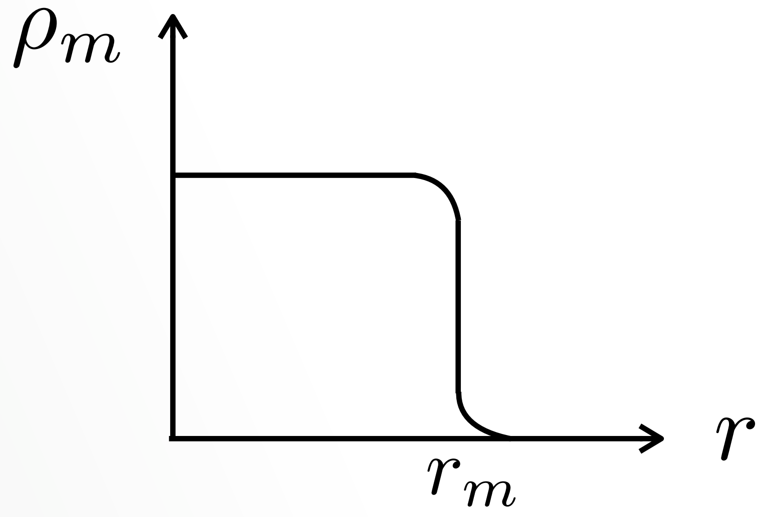
Interaction $h_{\text{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$

describes radial distribution of μ ;
point-nucleus, $F(r) = 1$

Ball, $F(r) = (r/r_m)^3$



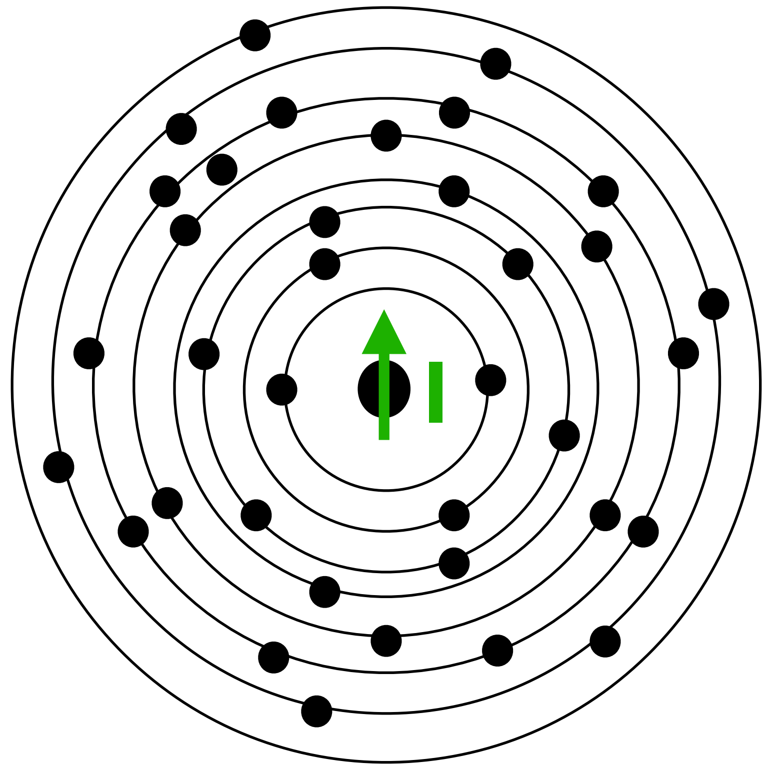
Fermi distribution



← Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\text{QED}}$

Modeling the hyperfine structure

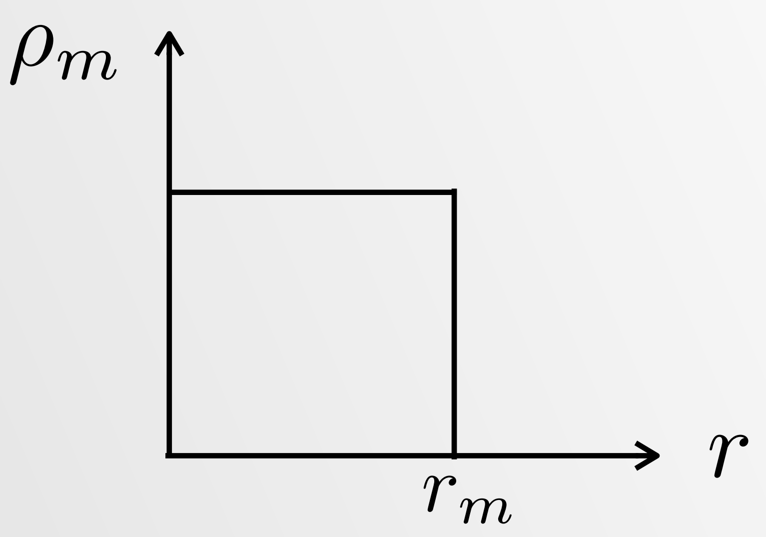


nuclear magnetic moment $\boldsymbol{\mu} = \mu \mathbf{I}/I$

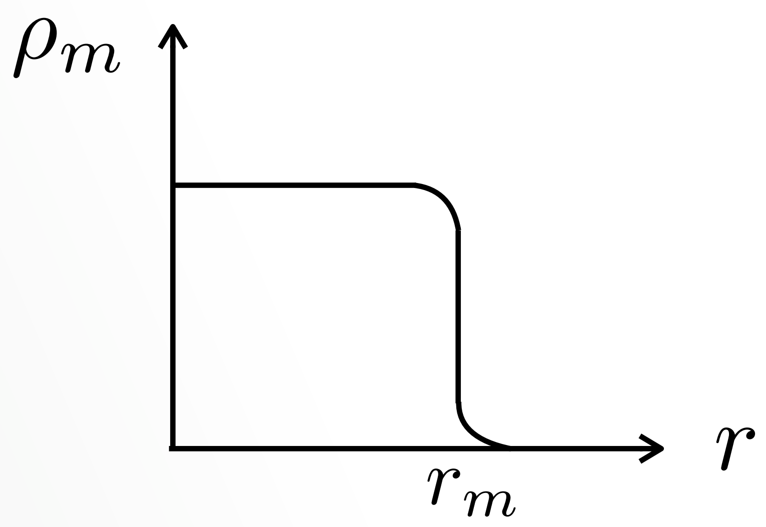
Interaction $h_{\rm hfs} = \dfrac{1}{c} \dfrac{\boldsymbol{\mu} \cdot (\mathbf{r} \times \boldsymbol{\alpha})}{r^3} F(r)$

describes radial distribution of μ ;
point-nucleus, $F(r) = 1$

Ball, $F(r) = (r/r_m)^3$



Fermi distribution

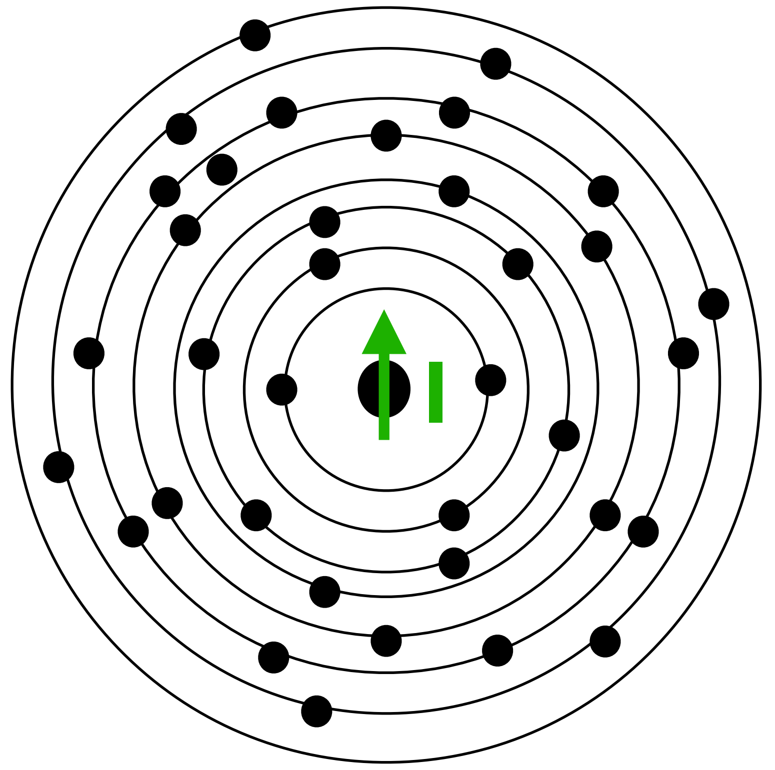


Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\rm QED}$

Many-body result,
finite nuclear charge effect included

Modeling the hyperfine structure

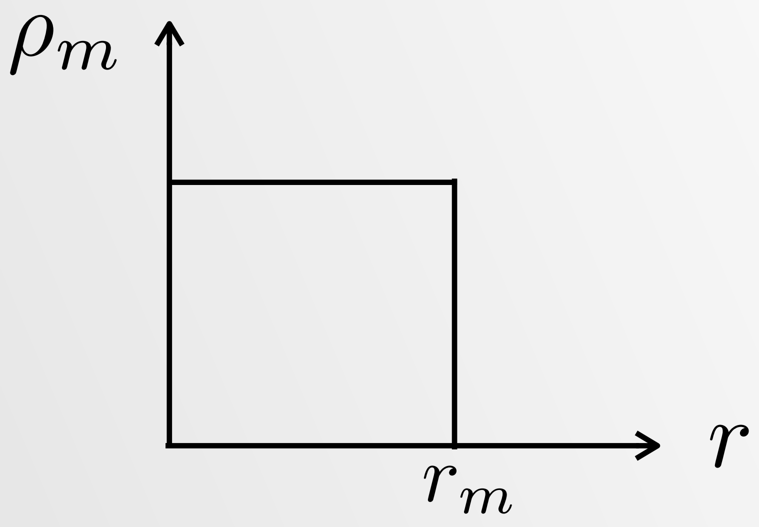


nuclear magnetic moment $\boldsymbol{\mu} = \mu \mathbf{I}/I$

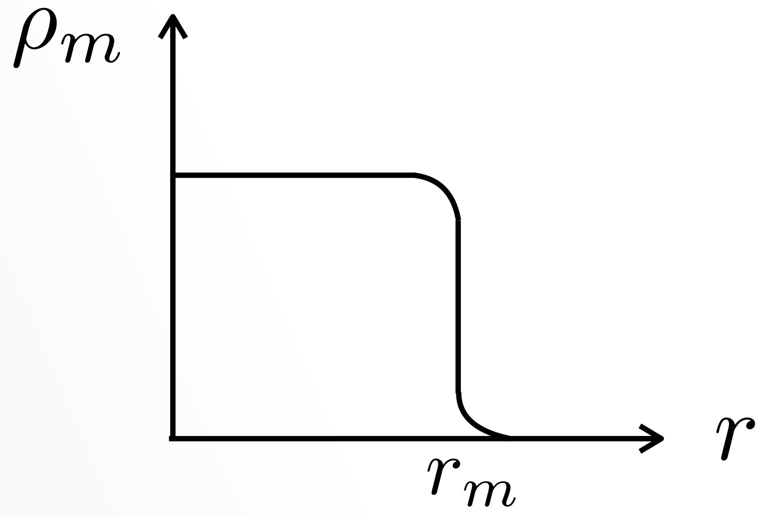
Interaction $h_{\text{hfs}} = \frac{1}{c} \frac{\boldsymbol{\mu} \cdot (\mathbf{r} \times \boldsymbol{\alpha})}{r^3} F(r)$

describes radial distribution of μ ;
point-nucleus, $F(r) = 1$

Ball, $F(r) = (r/r_m)^3$



Fermi distribution

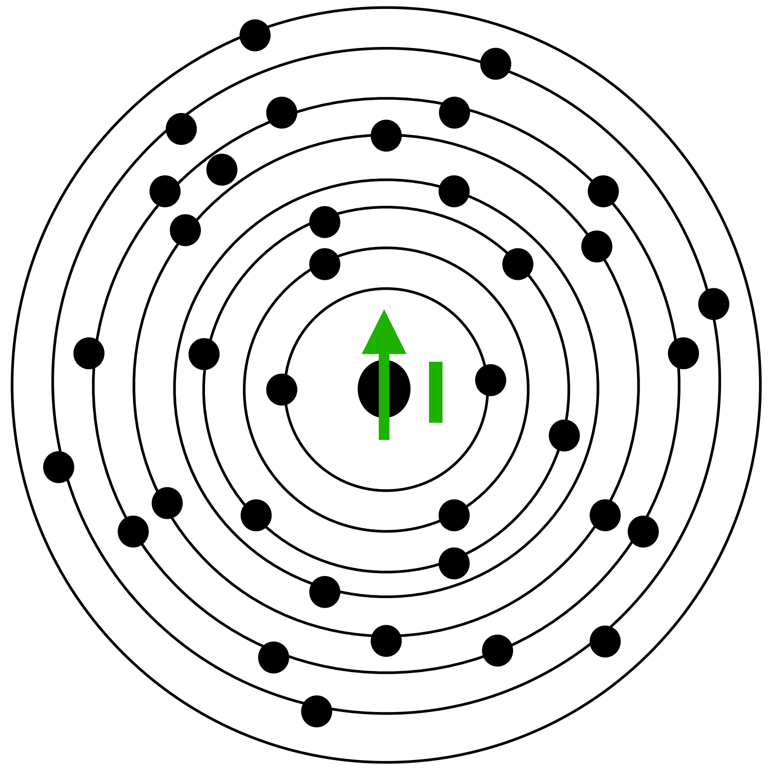


Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1 + \epsilon) + \delta A^{\text{QED}}$

Bohr-Weisskopf (BW) effect or *magnetic hyperfine anomaly*
— finite nuclear magnetisation contribution

Modeling the hyperfine structure

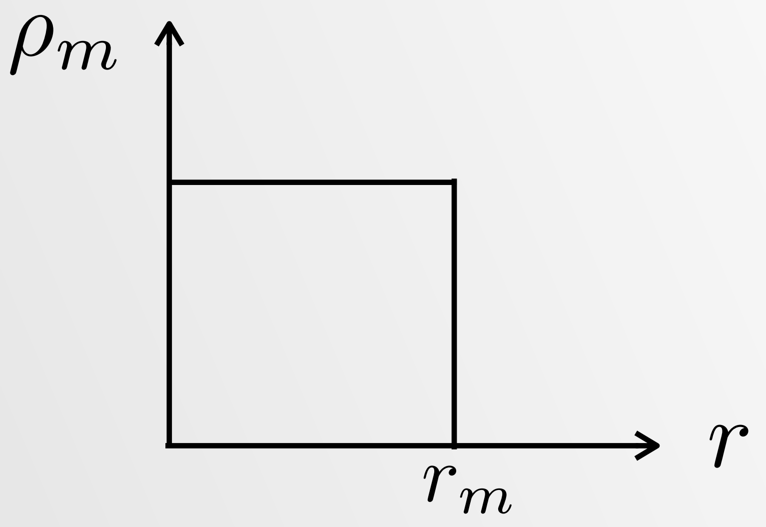


nuclear magnetic moment $\mu = \mu \mathbf{I}/I$

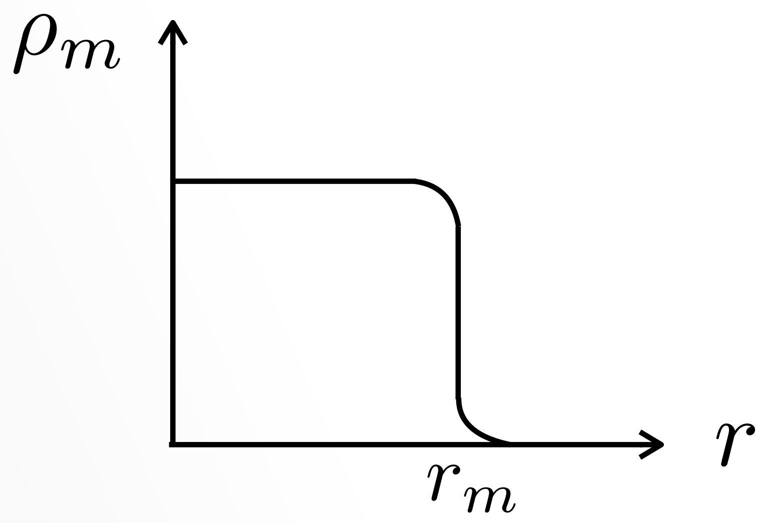
Interaction $h_{\mathrm{hfs}} = \frac{1}{c}\frac{\boldsymbol{\mu}\cdot(\mathbf{r}\times\boldsymbol{\alpha})}{r^3}F(r)$

describes radial distribution of μ ;
point-nucleus, $F(r) = 1$

Ball, $F(r) = (r/r_m)^3$



Fermi distribution

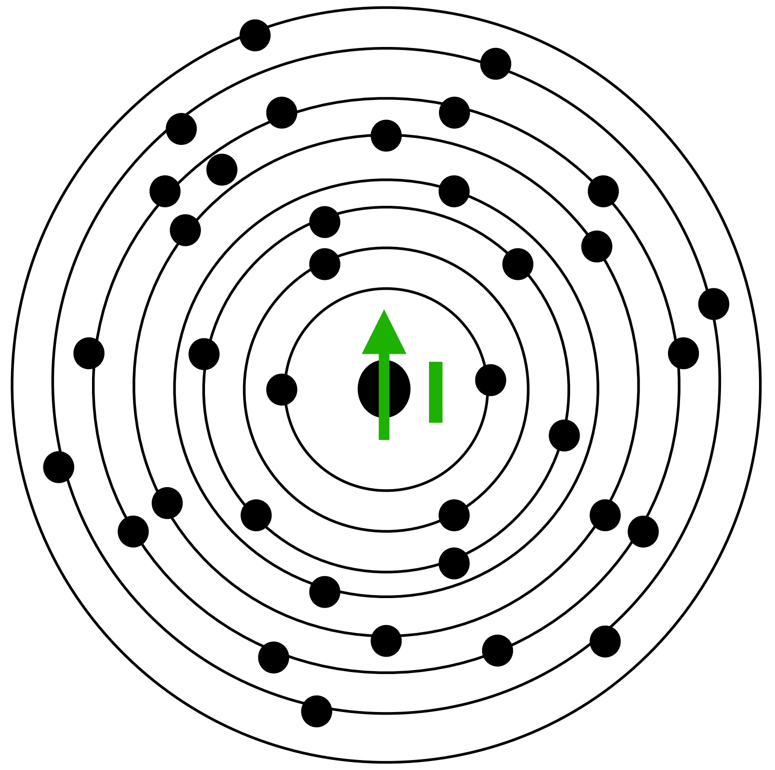


Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$

Quantum electrodynamics
radiative correction

Modeling the hyperfine structure

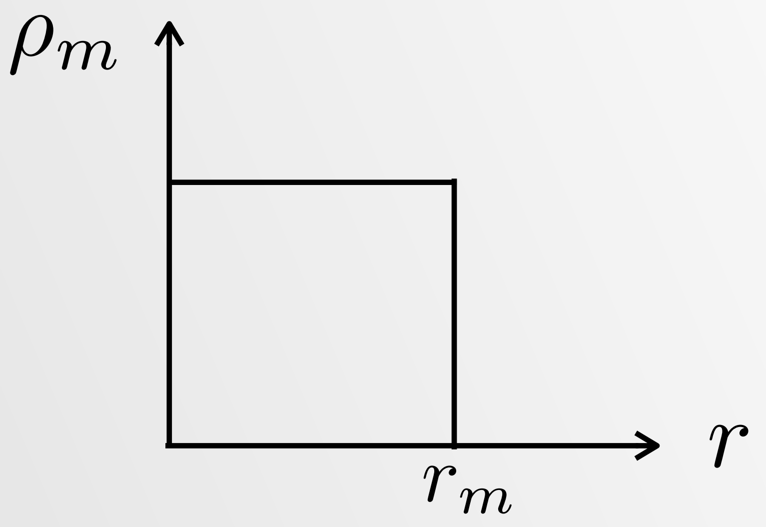


nuclear magnetic moment $\boldsymbol{\mu} = \mu \mathbf{I}/I$

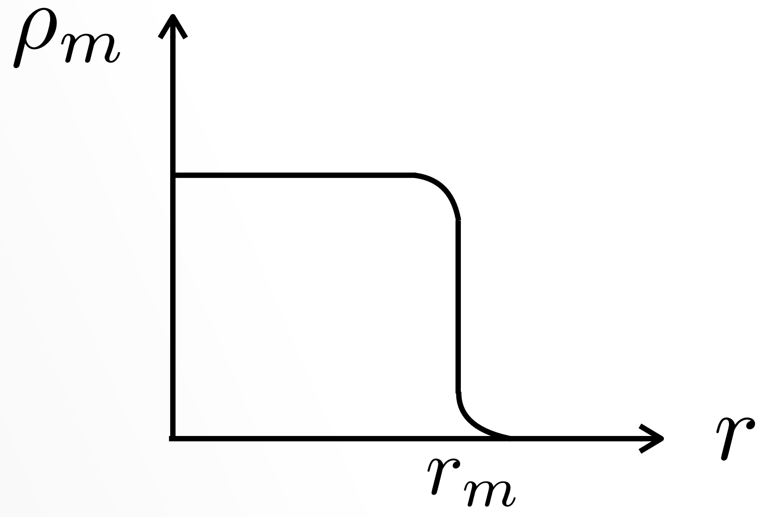
Interaction $h_{\text{hfs}} = \frac{1}{c} \frac{\boldsymbol{\mu} \cdot (\mathbf{r} \times \boldsymbol{\alpha})}{r^3} F(r)$

describes radial distribution of μ ;
point-nucleus, $F(r) = 1$

Ball, $F(r) = (r/r_m)^3$



Fermi distribution



Standard ways to model *F(r)*, until recently

Hyperfine splitting quantified by hyperfine constant *A*, $A = A_0(1 + \epsilon) + \delta A^{\text{QED}}$

contains factor μ

Hyperfine comparisons

$$A^{\mathrm{expt}} \longleftrightarrow A_0(1+\epsilon) + \delta A^{\mathrm{QED}}$$

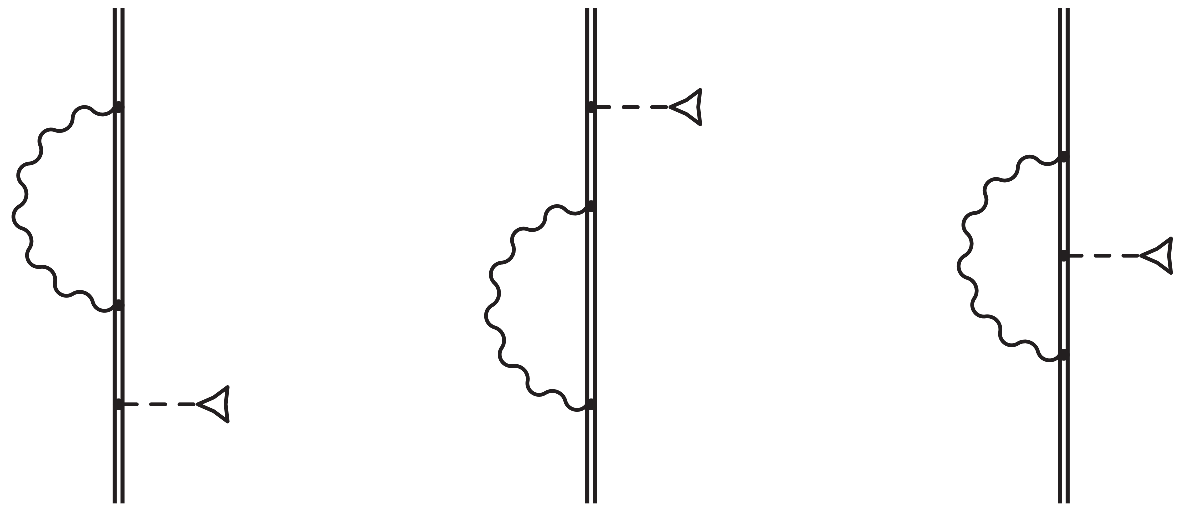
Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/ contributions are known well (< 0.1% uncertainty):

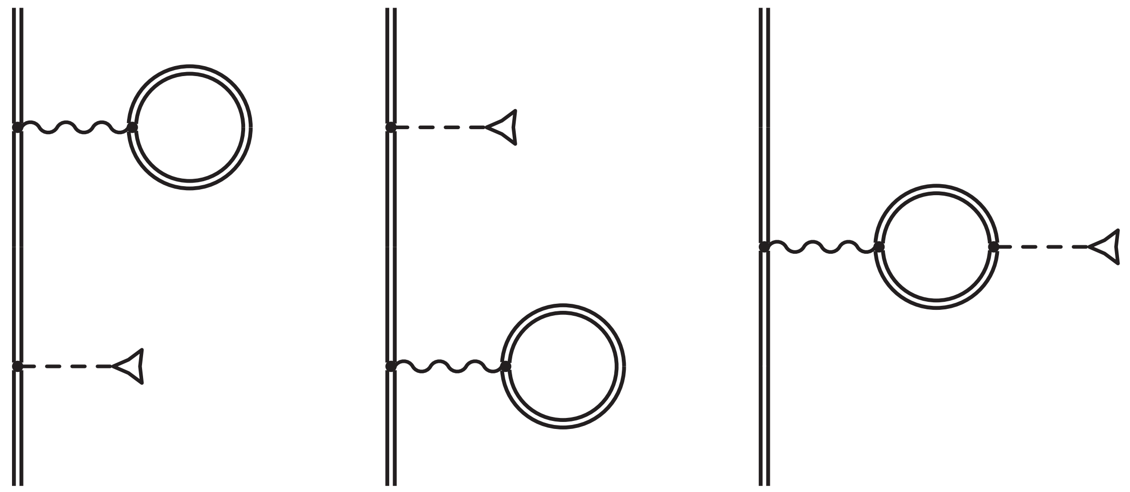
- QED radiative corrections δA^{QED}
- Nuclear magnetic moments μ
- Bohr-Weisskopf effect ϵ

Hyperfine comparisons

$$A^{\text{expt}} \longleftrightarrow A_0(1+\epsilon) + \delta A^{\text{QED}}$$

self energy





vacuum polarization

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/contributions are known well (< 0.1% uncertainty):

- ➤ QED radiative corrections δA^{QED}
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ

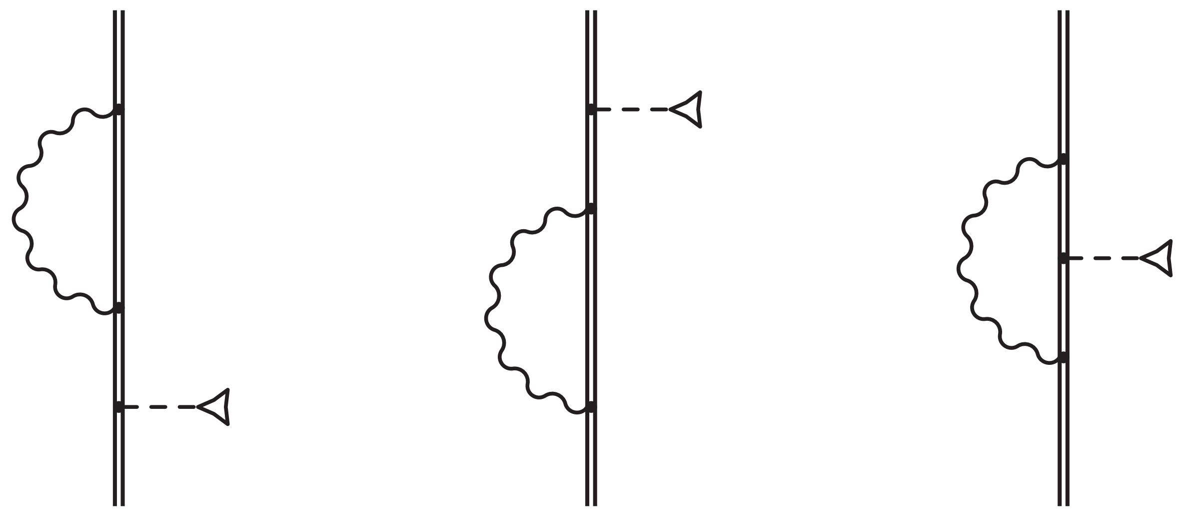
QED corrections to g.s. hyperfine constants (%)

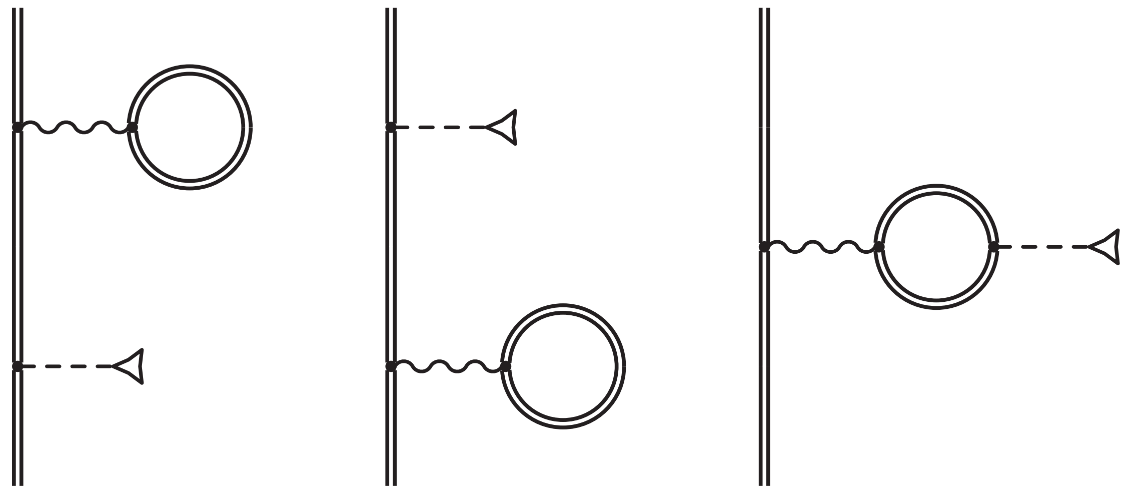
Cs	Ba^+	Fr	Ra^+	Reference
-0.38(6)	-0.37(4)	-0.60(1)	-0.55(8)	Ginges, Volotka, Fritzsche, PRA (2017)
-0.42		-0.6		Sapirstein and Cheng, PRA (2003)

Hyperfine comparisons

$$A^{\rm expt} \longleftrightarrow A_0(1+\epsilon) + \delta A^{\rm QED}$$

self energy





vacuum polarization

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/ contributions are known well (< 0.1% uncertainty):

- ➤ QED radiative corrections $\delta A^{\rm QED}$ ✅
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ

QED corrections to g.s. hyperfine constants (%)

Cs	Ba^+	Fr	Ra^+	Reference
-0.38(6)	-0.37(4)	-0.60(1)	-0.55(8)	Ginges, Volotka, Fritzsche, PRA (2017)
-0.42		-0.6		Sapirstein and Cheng, PRA (2003)

Hyperfine comparisons

$$A^{\text{expt}} \longleftrightarrow A_0(1+\epsilon) + \delta A^{\text{QED}}$$

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/contributions are known well ($<0.1\%$ uncertainty):

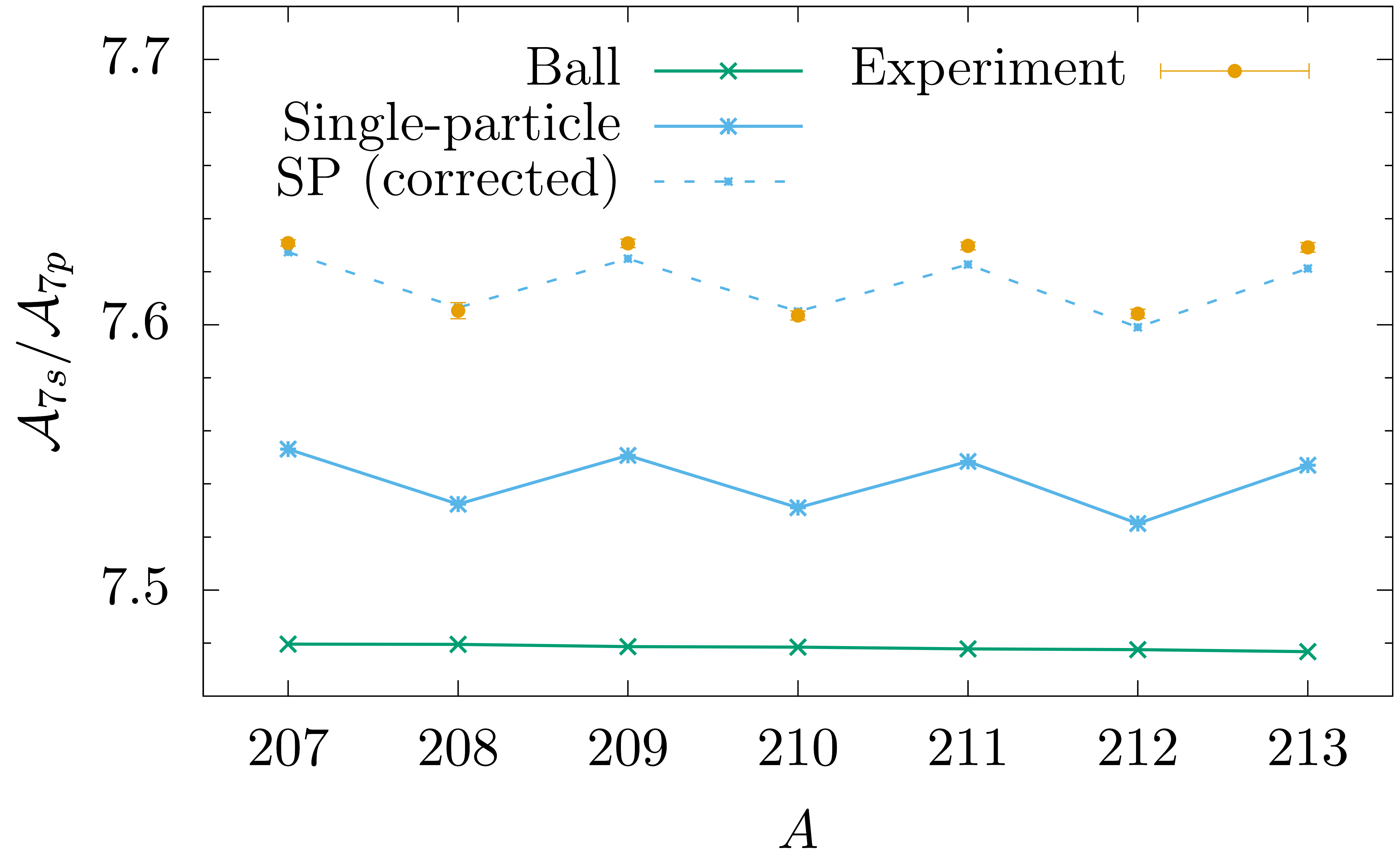
- ➤ QED radiative corrections δA^{QED}
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ

Known with 1-2% uncertainty for Fr isotopes.
We can do better!

$$A^{\text{expt}} \longleftrightarrow A^{\text{th}}(\mu_{\text{th}})(\mu/\mu_{\text{th}})$$

Found μ with 0.5% uncertainty

$A(7s)/A(7p_{1/2})$ vs atomic mass for francium



Roberts and Ginges, PRL (2020)
Experimental values: FrPNC collaboration

Hyperfine comparisons

$$A^{\text{expt}} \longleftrightarrow A_0(1+\epsilon) + \delta A^{\text{QED}}$$

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/contributions are known well (< 0.1% uncertainty):

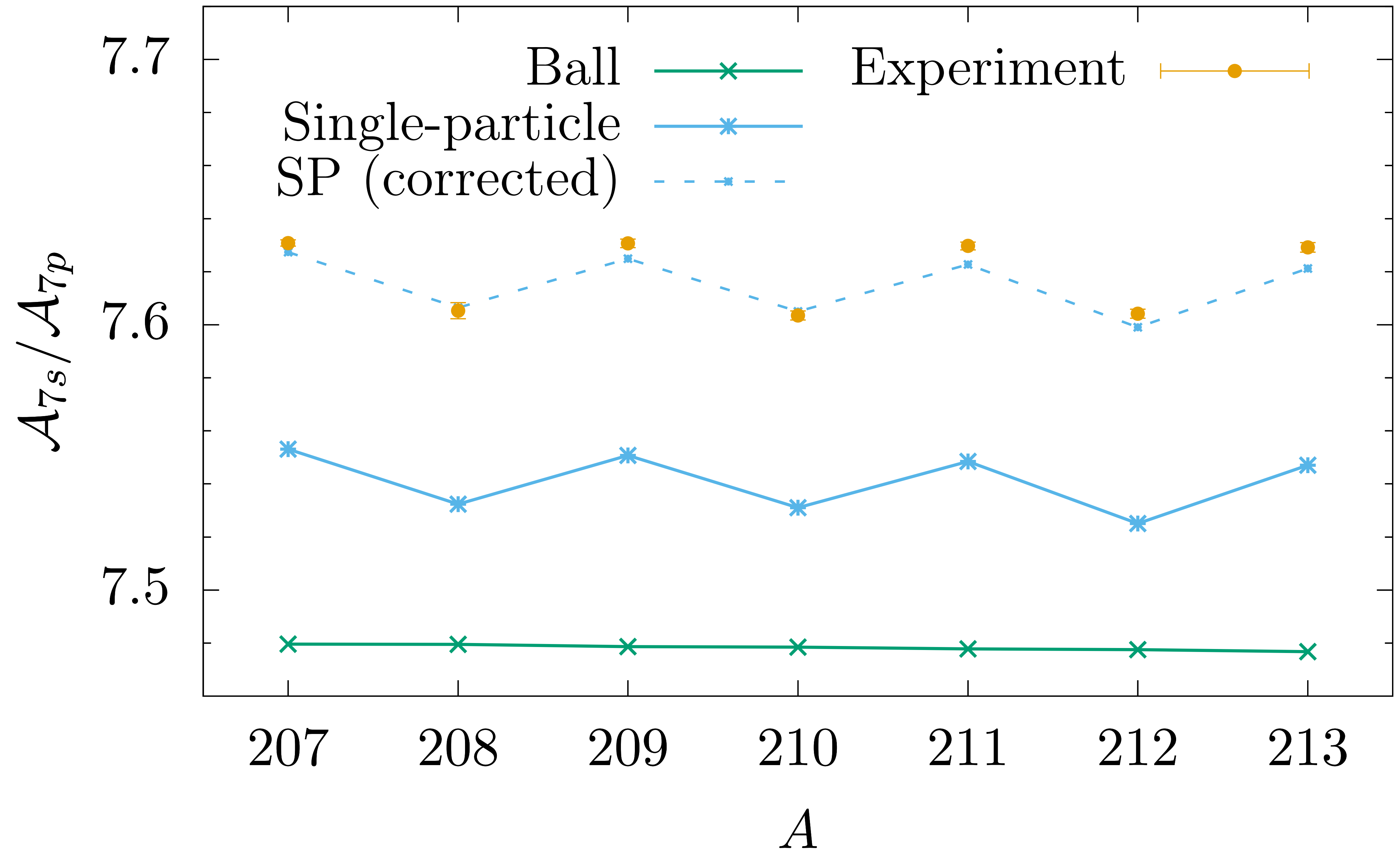
- ➤ QED radiative corrections δA^{QED}
- ➤ Nuclear magnetic moments μ ✅
- ➤ Bohr-Weisskopf effect ϵ

Known with 1-2% uncertainty for Fr isotopes.
We can do better!

$$A^{\text{expt}} \longleftrightarrow A^{\text{th}}(\mu_{\text{th}})(\mu/\mu_{\text{th}})$$

Found μ with 0.5% uncertainty

$A(7s)/A(7p_{1/2})$ vs atomic mass for francium



Roberts and Ginges, PRL (2020)
Experimental values: FrPNC collaboration

Hyperfine comparisons

$$A^{\text{expt}} \longleftrightarrow A_0(1+\epsilon) + \delta A^{\text{QED}}$$

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/ contributions are known well (< 0.1% uncertainty):

- ➤ QED radiative corrections δA^{QED}
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ

SP model:

$$F(r) = \left(\frac{r}{r_m}\right)^3 \left[1 - 3\ln\left(\frac{r}{r_m}\right)\frac{\mu_N}{\mu}\left(-\frac{2I-1}{8(I+1)}g_S + \frac{2I-1}{2}g_L\right)\right]$$

for $I=L+1/2$

BW corrections (%) to hyperfine constants

nuclear model	^{133}Cs	^{135}Ba^{+}	^{211}Fr	^{225}Ra^{+}
ball	-0.71	-0.74	-2.7	-2.8
single-particle (SP)	-0.21	-1.0	-1.3	-2.8
SP (WS, spin-orbit)	-0.19(14)	-1.3(4)	-1.4(5)	-4.3(13)

Difference **0.5%** **1.3%**

Ginges, Volotka, Fritzsche , PRA (2017)

Hyperfine comparisons

$$A^{\text{expt}} \longleftrightarrow A_0(1+\epsilon) + \delta A^{\text{QED}}$$

Provides test of atomic many-body theory in the nuclear vicinity *only if* the following properties/ contributions are known well (< 0.1% uncertainty):

- ➤ QED radiative corrections δA^{QED}
- ➤ Nuclear magnetic moments μ
- ➤ Bohr-Weisskopf effect ϵ ❌

SP model:

$$F(r) = \left(\frac{r}{r_m}\right)^3 \left[1 - 3\ln\left(\frac{r}{r_m}\right)\frac{\mu_N}{\mu}\left(-\frac{2I-1}{8(I+1)}g_S + \frac{2I-1}{2}g_L\right)\right]$$

for $I=L+1/2$

BW corrections (%) to hyperfine constants

nuclear model	^{133}Cs	^{135}Ba$^+$	^{211}Fr	^{225}Ra$^+$
ball	-0.71	-0.74	-2.7	-2.8
single-particle (SP)	-0.21	-1.0	-1.3	-2.8
SP (WS, spin-orbit)	-0.19(14)	-1.3(4)	-1.4(5)	-4.3(13)

Difference **0.5%** **1.3%**

Ginges, Volotka, Fritzsche , PRA (2017)

Total hyperfine intervals

Calculations of hyperfine intervals and comparison with experiment. Units: MHz

	^{133}Cs	$^{135}Ba^+$	^{211}Fr	$^{225}Ra^+$
Many-body	9229.5	7286.8	45374	-29113
BW	-17.0(131)	-91.8(275)	-641(244)	1267(380)
QED	-35.1(58)	-27.1(30)	-273(56)	159(23)
Total theory	9177.4	7167.9	44460	-27687
Experiment	9192.6	7183.3	43570	-27731
Difference	-15.2	-15.4	890	44
Difference (%)	-0.17(16)	-0.21(38)	2.0(6)(20)	-0.2(14)

Ginges, Volotka, Fritzsche, PRA (2017)

Extraction of Ra^+ BW effect, -4.7%: Skripnikov, J. Chem. Phys. (2020)

And from molecules! RaF S. Wilkins et al., arxiv:2311.04121

Differential hyperfine anomaly

Ratio of hyperfine constants of different isotopes of same element:

$$\mathcal{A}^{(1)}/\mathcal{A}^{(2)} = g_I^{(1)}/g_I^{(2)}(1 + {}^1\Delta^2)$$

Typically for nuclei of different spin: ${}^1\Delta^2 \approx \epsilon^{(1)} - \epsilon^{(2)}$

→ Gives *difference* in BW effect for different isotopes

		Isotope 1				Isotope 2				Differential anomaly ${}^1\Delta^2$ (%)		
		A	I^π	$\epsilon_{\rm Ball}$ (%)	$\epsilon_{\rm SP}$ (%)	A	I^π	$\epsilon_{\rm Ball}$ (%)	$\epsilon_{\rm SP}$ (%)	Ball	SP	Expt. [59]
$_{37}$Rb	$5s_{1/2}$	85	$5/2^-$	−0.306	0.044	87	$3/2^-$	−0.306	−0.278	−0.001	0.323	0.35142(30)
						86	2^-	−0.306	−0.139	0.000	0.183	0.17(9)
$_{47}$Ag	$5s_{1/2}$	107	$1/2^-$	−0.497	−4.20	103	$7/2^+$	−0.493	−0.347	−0.018	−3.88	−3.4(17)
						109	$1/2^-$	−0.498	−3.78	0.007	−0.431	−0.41274(29)
$_{55}$Cs	$6s_{1/2}$	133	$7/2^+$	−0.716	−0.209	131	$5/2^+$	−0.716	−0.596	−0.001	0.389	0.45(5) [a]
						135	$7/2^+$	−0.716	−0.247	0.002	0.039	0.037(9) [b]
						134	4^+	−0.716	−0.371	0.000	0.163	0.169(30)
$_{56}$Ba$^+$	$6s_{1/2}$	135	$3/2^+$	−0.747	−1.03	137	$3/2^+$	−0.747	−1.03	0.001	0.001	−0.191(5)

Roberts and Ginges, PRA (2021)

Expt. data from: Persson, At. Data Nucl. Data Tables (2013)

BW effect — properties

Relative BW correction

$$\epsilon = \frac{\int_0^{r_m} dr\, f(r) g(r) [F(r) - 1]/r^2}{\int_0^{\infty} dr\, f(r) g(r)/r^2}$$

Shabaev et al., PRL (2001)
Skripnikov, J. Chem. Phys. (2020)
Roberts, Ranclaud, Ginges, PRA (2022)

BW effect — properties

Relative BW correction

$$\epsilon = \frac{\int_0^{r_m} dr f(r) g(r) [F(r) - 1]/r^2}{\int_0^{\infty} dr f(r) g(r)/r^2}$$

- In the nuclear region, the electrons see the unscreened Coulomb field of the nucleus

- Since the binding energies $\varepsilon \ll V(r)$, wave functions with the same angular dependence are proportional.

$$\begin{bmatrix} V(r) - \varepsilon & c(\kappa/r - \partial_r) \\ c(\kappa/r + \partial_r) & V(r) - \varepsilon - 2c^2 \end{bmatrix} \begin{bmatrix} f_{n\kappa} \\ g_{n\kappa} \end{bmatrix} = 0$$

Shabaev et al., PRL (2001)
Skripnikov, J. Chem. Phys. (2020)
Roberts, Ranclaud, Ginges, PRA (2022)

BW effect — properties

Relative BW correction

$$\epsilon = \frac{\int_0^{r_m} dr f(r) g(r) [F(r) - 1]/r^2}{\int_0^{\infty} dr f(r) g(r)/r^2}$$

- In the nuclear region, the electrons see the unscreened Coulomb field of the nucleus
- Since the binding energies $\varepsilon \ll V(r)$, wave functions with the same angular dependence are proportional.

$$\begin{bmatrix} V(r) - \varepsilon & c(\kappa/r - \partial_r) \\ c(\kappa/r + \partial_r) & V(r) - \varepsilon - 2c^2 \end{bmatrix} \begin{bmatrix} f_{n\kappa} \\ g_{n\kappa} \end{bmatrix} = 0$$

BW effect is independent of principal quantum number!

$$\Rightarrow \quad \epsilon_{n\kappa} = \epsilon_{n'\kappa}$$

Shabaev et al., PRL (2001)
Skripnikov, J. Chem. Phys. (2020)
Roberts, Ranclaud, Ginges, PRA (2022)

BW effect — properties

Relative BW correction

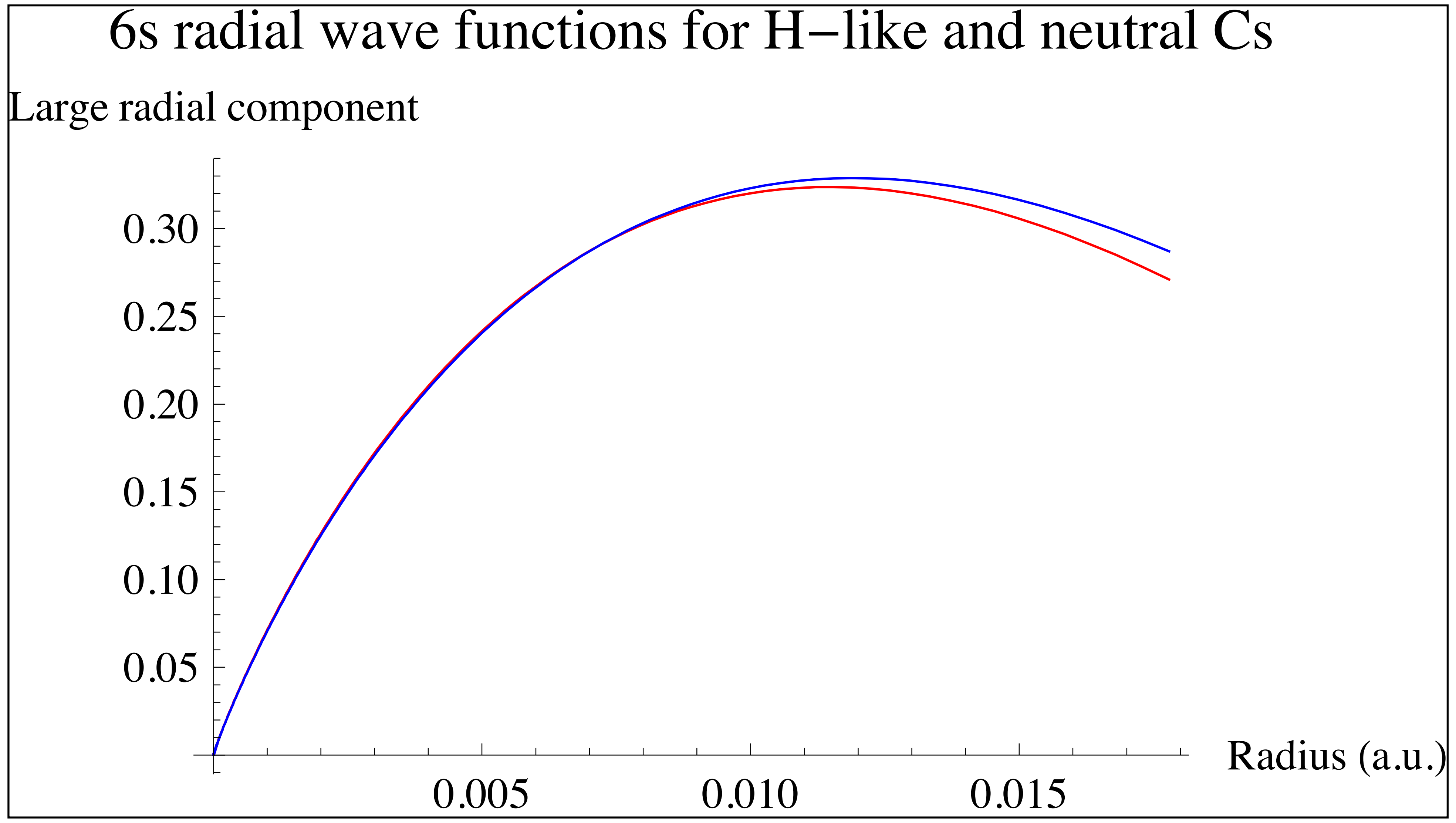
$$\epsilon = \frac{\int_0^{r_m} dr\, f(r) g(r)[F(r) - 1]/r^2}{\int_0^{\infty} dr\, f(r) g(r)/r^2}$$

- In the nuclear region, the electrons see the unscreened Coulomb field of the nucleus
- Since the binding energies $\varepsilon \ll V(r)$, wave functions with the same angular dependence are proportional.

$$\begin{bmatrix} V(r) - \varepsilon & c(\kappa/r - \partial_r) \\ c(\kappa/r + \partial_r) & V(r) - \varepsilon - 2c^2 \end{bmatrix} \begin{bmatrix} f_{n\kappa} \\ g_{n\kappa} \end{bmatrix} = 0$$

BW effect is independent of principal quantum number!

$$\Rightarrow \quad \epsilon_{n\kappa} = \epsilon_{n'\kappa}$$



Also, in the nuclear region, for heavy systems:

$$f_{s_{1/2}} \propto g_{p_{1/2}} \quad , \quad g_{s_{1/2}} \propto f_{p_{1/2}}$$

BW effects in atoms related to BW matrix element for *1s* state of H-like ion

Shabaev et al., PRL (2001)
Skripnikov, J. Chem. Phys. (2020)
Roberts, Ranclaud, Ginges, PRA (2022)

BW effect: ratio method

By taking a ratio of two states with different principal quantum number, dependence on BW effect may be removed!

$$A_{n\kappa}^{\rm th} = A_{0,n\kappa}\left(A_{n'\kappa}^{\rm exp}/A_{0,n'\kappa}\right)$$

May be used to make high-precision predictions of the hyperfine constants!

Ratio method: Ginges and Volotka, PRA (2018)

BW effect: ratio method

By taking a ratio of two states with different principal quantum number, dependence on BW effect may be removed!

$$A^{\rm th}_{n\kappa} = A_{0,n\kappa}\left(A^{\rm exp}_{n'\kappa}/A_{0,n'\kappa}\right)$$

May be used to make high-precision predictions of the hyperfine constants!

From Quirk et al., PRA (2022)
[Dan Elliott group, Purdue]

	$A_{\rm hfs}$ (MHz)			
	Experiment		Theory	
State	This work	Prior expt.	Ref. [37]	Ref. [16]
12*s*	26.318 (15)	26.31 (10) [24]	26.28	26.30 (2)
13*s*	18.431 (10)	18.40 (11) [25]		18.42 (1)

Ref. [16] : Grunefeld, Roberts, Ginges, PRA (2019)

from Quirk et al., PRA (2023)
[Dan Elliott group, Purdue]

$A_{\rm hfs}$ (MHz) for $8p_{1/2}$

A	Source
Experiment	
42.97 (10)	Tai *et al.*, 1973 [40]
42.92 (25)	Cataliotti *et al.*, 1996 [48]
42.95 (25)	Liu & Baird, 2000 [49]
42.933 (8)	This work
Theory	
42.43	Safronova *et al.*, 1999 [46]
42.32	Tang *et al.*, 2019 [47]
42.95 (9)	fit method, Grunefeld *et al.*, 2019 [34]
42.93 (7)	ratio method, Grunefeld *et al.*, 2019 [34]

Ratio method: Ginges and Volotka, PRA (2018)

BW effect: from H-like ion

$$\mathcal{A}^{\rm 1s}_{\rm expt} = \mathcal{A}^{1s}_0(1+\epsilon^{1s}) + \delta\mathcal{A}^{1s}_{\rm QED}$$

BW effect with $\sim 1\%$ uncertainty from H-like ^{203,205}Tl, ^{207}Pb, ^{209}Bi

BW effect: from H-like ion

$$\mathcal{A}^{1s}_{\rm expt} = \mathcal{A}^{1s}_0(1+\epsilon^{1s}) + \delta\mathcal{A}^{1s}_{\rm QED}$$

BW effect with $\sim 1\%$ uncertainty from H-like ^{203,205}Tl, ^{207}Pb, ^{209}Bi

H-like ion result may be used to find BW effect in many-electron atoms!

$$\mathcal{A} = \mathcal{A}_0(1 + x_{\rm scr}\,\epsilon^{1s}) + \delta\mathcal{A}_{\rm QED}$$

↑

electronic
screening factor

$x_{\rm scr}$ *independent of the nuclear model!*

s states: $x_{\rm scr} \approx 1$, negligible uncertainty

Roberts, Ranclaud, Ginges, PRA (2022)

BW effect: from H-like ion

$$\mathcal{A}^{1\mathrm{s}}_{\mathrm{expt}} = \mathcal{A}^{1s}_0(1+\epsilon^{1s}) + \delta\mathcal{A}^{1s}_{\mathrm{QED}}$$

BW effect with $\sim 1\%$ uncertainty from H-like ^{203,205}Tl, ^{207}Pb, ^{209}Bi

H-like ion result may be used to find BW effect in many-electron atoms!

$$\mathcal{A} = \mathcal{A}_0(1 + x_{\mathrm{scr}}\,\epsilon^{1s}) + \delta\mathcal{A}_{\mathrm{QED}}$$

↑

electronic
screening factor

x_{scr} *independent of the nuclear model!*

s states: $x_{\mathrm{scr}} \approx 1$, negligible uncertainty

Nuclear structure uncertainty is entirely removed from atomic calculations!

Roberts, Ranclaud, Ginges, PRA (2022)

BW effect: from H-like ion

$$\mathcal{A}^{1s}_{\rm expt} = \mathcal{A}^{1s}_0(1+\epsilon^{1s}) + \delta\mathcal{A}^{1s}_{\rm QED}$$

BW effect with $\sim 1\%$ uncertainty from H-like ^{203,205}Tl, ^{207}Pb, ^{209}Bi

H-like ion result may be used to find BW effect in many-electron atoms!

$$\mathcal{A} = \mathcal{A}_0(1 + x_{\rm scr}\,\epsilon^{1s}) + \delta\mathcal{A}_{\rm QED}$$

↑ electronic screening factor

$x_{\rm scr}$ *independent of the nuclear model!*

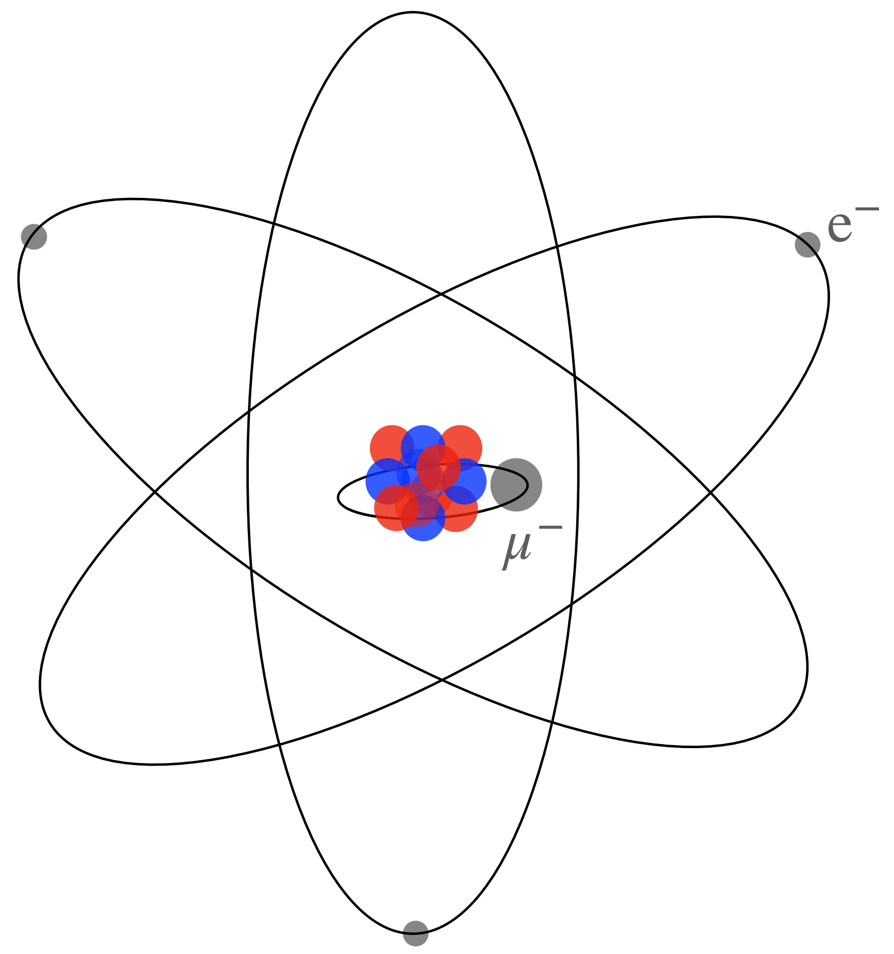
s states: $x_{\rm scr} \approx 1$, negligible uncertainty

Nuclear structure uncertainty is entirely removed from atomic calculations!

Roberts, Ranclaud, Ginges, PRA (2022)

from muonic atom experiment

Historical data on muonic hyperfine structure for Cs!



BW effect: from H-like ion

$$\mathcal{A}^{1s}_{\rm expt} = \mathcal{A}^{1s}_0(1+\epsilon^{1s}) + \delta\mathcal{A}^{1s}_{\rm QED}$$

BW effect with $\sim 1\%$ uncertainty from H-like ^{203,205}Tl, ^{207}Pb, ^{209}Bi

H-like ion result may be used to find BW effect in many-electron atoms!

$$\mathcal{A} = \mathcal{A}_0(1 + x_{\rm scr}\,\epsilon^{1s}) + \delta\mathcal{A}_{\rm QED}$$

↑ electronic screening factor

$x_{\rm scr}$ *independent of the nuclear model!*

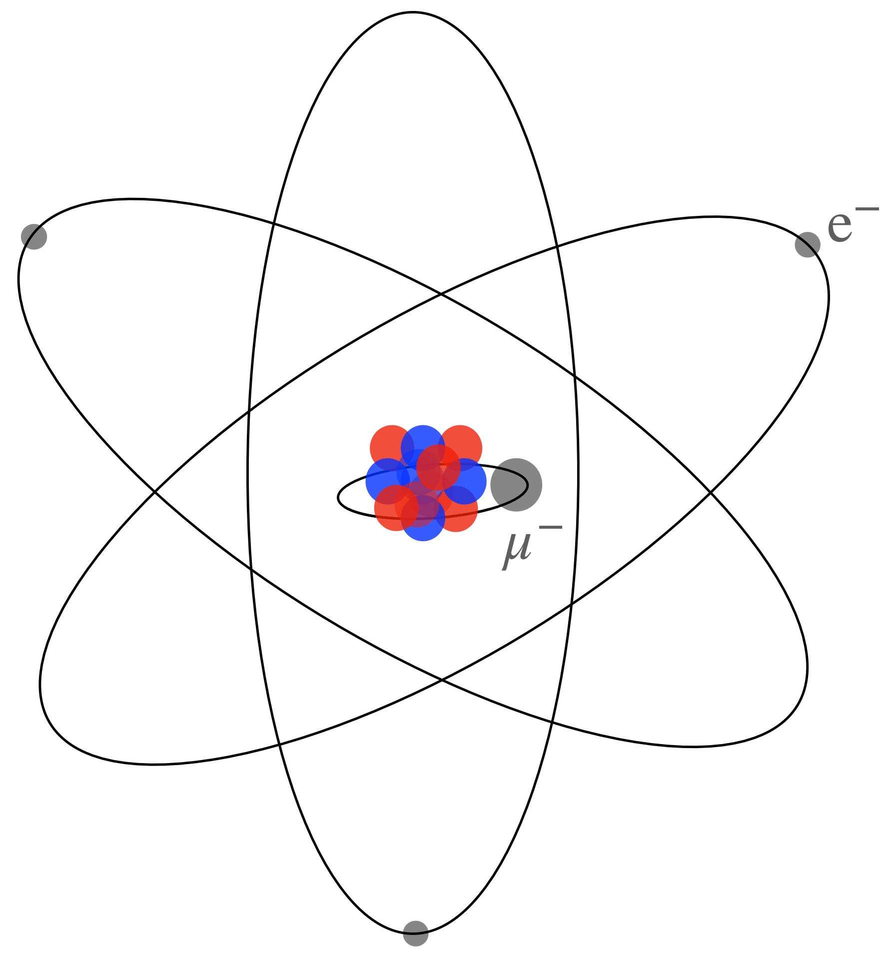
s states: $x_{\rm scr} \approx 1$, negligible uncertainty

Nuclear structure uncertainty is entirely removed from atomic calculations!

Roberts, Ranclaud, Ginges, PRA (2022)

from muonic atom experiment

Historical data on muonic hyperfine structure for Cs!



Proposed and implemented method to extract BW effect in muonic Cs and translate to Cs

Elizarov et al., Opt. Spectrosc. (2006)
Sanamyan, Roberts, Ginges, PRL (2023)

BW effect: from H-like ion

$$\mathcal{A}^{1s}_{\rm expt} = \mathcal{A}^{1s}_0(1+\epsilon^{1s}) + \delta\mathcal{A}^{1s}_{\rm QED}$$

BW effect with $\sim 1\%$ uncertainty from H-like ^{203,205}Tl, ^{207}Pb, ^{209}Bi

H-like ion result may be used to find BW effect in many-electron atoms!

$$\mathcal{A} = \mathcal{A}_0(1 + x_{\rm scr}\,\epsilon^{1s}) + \delta\mathcal{A}_{\rm QED}$$

↑ electronic screening factor

$x_{\rm scr}$ *independent of the nuclear model!*

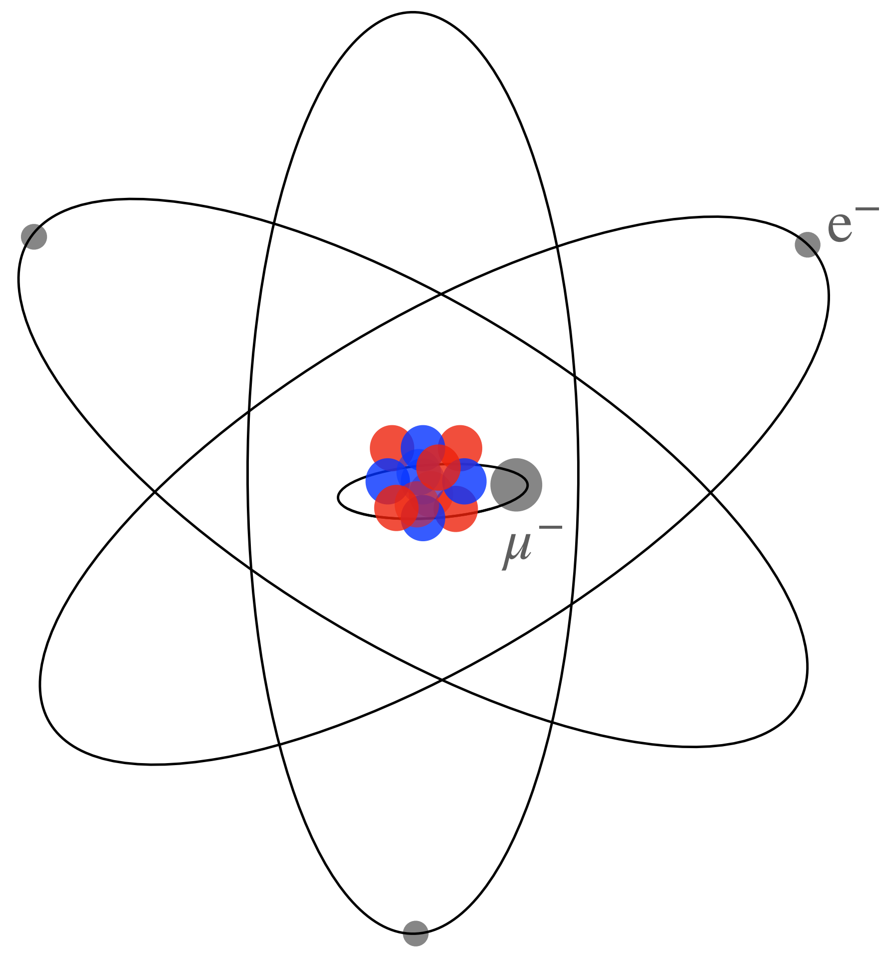
s states: $x_{\rm scr} \approx 1$, negligible uncertainty

Nuclear structure uncertainty is entirely removed from atomic calculations!

Roberts, Ranclaud, Ginges, PRA (2022)

from muonic atom experiment

Historical data on muonic hyperfine structure for Cs!



Proposed and implemented method to extract BW effect in muonic Cs and translate to Cs

Cs atom — SP model: -0.21%
SP(WS) model: -0.19(14)%
“ball”/fermi model: -0.7%

Elizarov et al., Opt. Spectrosc. (2006)
Sanamyan, Roberts, Ginges, PRL (2023)

BW effect: from H-like ion

$$\mathcal{A}^{1s}_{\rm expt} = \mathcal{A}^{1s}_0(1+\epsilon^{1s}) + \delta\mathcal{A}^{1s}_{\rm QED}$$

BW effect with $\sim 1\%$ uncertainty from H-like ^{203,205}Tl, ^{207}Pb, ^{209}Bi

H-like ion result may be used to find BW effect in many-electron atoms!

$$\mathcal{A} = \mathcal{A}_0(1 + x_{\rm scr}\,\epsilon^{1s}) + \delta\mathcal{A}_{\rm QED}$$

↑
electronic
screening factor

$x_{\rm scr}$ *independent of the nuclear model!*

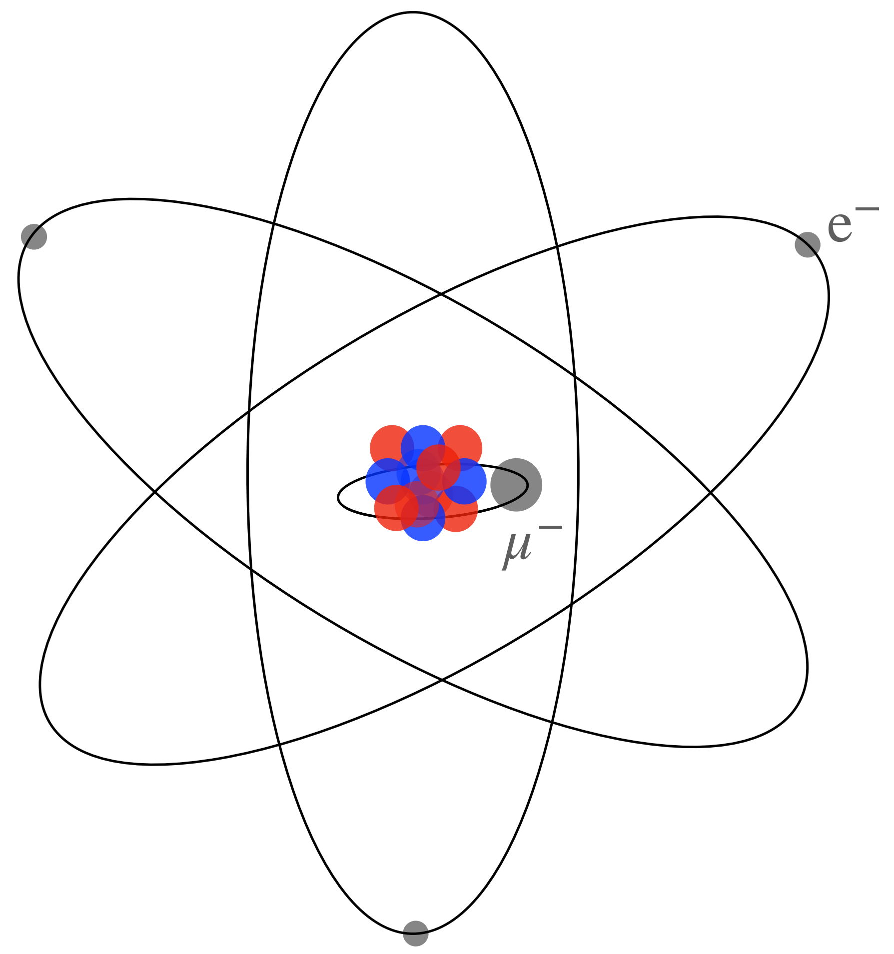
s states: $x_{\rm scr} \approx 1$, negligible uncertainty

Nuclear structure uncertainty is entirely removed from atomic calculations!

Roberts, Ranclaud, Ginges, PRA (2022)

from muonic atom experiment

Historical data on muonic hyperfine structure for Cs!



Proposed and implemented method to extract BW effect in muonic Cs and translate to Cs

Cs atom — SP model: -0.21%
SP(WS) model: -0.19(14)%
"ball"/fermi model: -0.7%

Empirically-deduced BW effect ($-\epsilon$) in %

	μ-atoms	H-like ions		Atoms
	μ exp	μ exp	H-like exp	μ exp
^{133}Cs	18(14)	0.23(17)	···	0.24(18)
^{203}Tl	50.8(1.6)	1.93(15)	2.21(8)	
^{205}Tl	51.8(8)	1.98(15)	2.25(8)	
^{209}Bi	28.8(3.9)	0.98(14)	1.03(5)	

Elizarov et al., Opt. Spectrosc. (2006)
Sanamyan, Roberts, Ginges, PRL (2023)

Bohr-Weisskopf effect summary

Accurate modelling of the finite magnetisation distribution in atomic nuclei is important for

- ➤ Hyperfine comparisons
    - Tests of atomic wave functions in the nuclear region
    - Reducing APV theory uncertainty to 0.1%
- ➤ Nuclear structure theory
- ➤ Determination of nuclear moments
- ➤ Probing the neutron distribution
- ➤ Tests of quantum electrodynamics

Summary

Atoms can be used to do breakthrough particle physics!

- Atomic parity violation
- Time-reversal-violating electric dipole moments

Lots of interdisciplinary discoveries that can be made on the way!

- Includes nuclear physics insights

Precision atomic theory

- Necessary and difficult! Though proceeding to reduce atomic theory uncertainties

Summary

Atoms can be used to do breakthrough particle physics!

- Atomic parity violation
- Time-reversal-violating electric dipole moments

Lots of interdisciplinary discoveries that can be made on the way!

- Includes nuclear physics insights

Precision atomic theory

- Necessary and difficult! Though proceeding to reduce atomic theory uncertainties

Summary

Atoms can be used to do breakthrough particle physics!

- Atomic parity violation
- Time-reversal-violating electric dipole moments

Lots of interdisciplinary discoveries that can be made on the way!

- Includes nuclear physics insights

Precision atomic theory

- Necessary and difficult! Though proceeding to reduce atomic theory uncertainties

Thank you!

Group members working on hyperfine anomaly

Current:
Ben Roberts (DECRA Fellow)
Giri Hiranandani (PhD student)
Zach Stevens-Hough (Honours student)

Previous:
Swaantje Grunefeld (Postdoc)
George Sanamyan (Research Assistant)
Perry Ranclaud (Honours student)
James Vandeleur (Honours student)

Collaborators:
Andrey Volotka (St Petersburg)
Stephan Fritzsche (Jena)
Magdalena Kowalska (ISOLDE)
Mark Bissell (ISOLDE)
Jacek Dobaczewski (York)
Markus Kortelainen (JYU)